10:41:15 OCA PAD AMENDMENT - PROJECT HEADER INFORMATION 03/04/91

Active

Project #: B-03-A13 Cost share #: Rev #: 1
Center # : 10/24-6-R6500-0B3 Center shr #: OCA file #: 126
Work type : RES
Contract#: F33615-87-D-0626-0013 Mod #: 01 Document : DO
Prime #: Contract entity: GTRC

Subprojects ? : N
Main project #:

Project unit: BEC Unit code: 03.010.203
Project director(s):
SHELTON W W BEC (404)894-8727

Sponsor/division names: AIR FORCE / WRIGHT-PATTERSON AFB, OH
Sponsor/division codes: 104 / 002

Award period: 900502 to 910302 (performance) 910502 (reports)

Sponsor amount	New this change	Total to date
Contract value	0.00	125,508.00
Funded	85,508.00	125,508.00
Cost sharing amount		0.00

Does subcontracting plan apply ?: Y

Title: DEVELOPMENT OF HIGH POWER MICROWAVE DEVICES FOR USE IN BIOEFFECTS STUDIES

PROJECT ADMINISTRATION DATA

OCA contact: E. Faith Gleason 894-4820

Sponsor technical contact

JAMES H MERRITT
(512)536-2439

RADIATION SCIENCES DIVISION
USAFSAM/RZP
BROOKS AFB TX 78235-5301

Sponsor issuing office

JOHN M. LIPKER
(513)255-5633

AFSC/ASD/PKRSC
WRIGHT-PATTERSON AFB OH 45433 6503

Security class (U,C,S,TS) : U ONR resident rep. is ACO (Y/N): Y
Defense priority rating : [illegible] See supplemental sheet
Equipment title vests with: Sponsor X GIT

Administrative comments -
* MOD 01 INCREASES FUNDING ALLOTMENT BY $85,508. THE ORDER IS NOW FULLY FUNDED

GEORGIA INSTITUTE OF TECHNOLOGY
OFFICE OF CONTRACT ADMINISTRATION

NOTICE OF PROJECT CLOSEOUT

Closeout Notice Date 07/07/92

Project No. B-03-A13 Center No. 10/24-6-R6500-0B3

Project Director SHELTON W W School/Lab BEC

Sponsor AIR FORCE/WRIGHT-PATTERSON AFB, OH

Contract/Grant No. F33615-87-D-0626-0013 Contract Entity GTRC

Prime Contract No. ____________________

Title DEVELOPMENT OF HIGH POWER MICROWAVE DEVICES FOR USE IN BIOEFFECTS STUDIES

Effective Completion Date 910302 (Performance) 910502 (Reports)

Closeout Actions Required:	Y/N	Date Submitted
Final Invoice or Copy of Final Invoice	Y	920413
Final Report of Inventions and/or Subcontracts	Y	
Government Property Inventory & Related Certificate	Y	
Classified Material Certificate	N	
Release and Assignment	Y	920422
Other ____________________	N	

Comments ____________________

Subproject Under Main Project No. ____________________

Continues Project No. ____________________

Distribution Required:

Project Director	Y
Administrative Network Representative	Y
GTRI Accounting/Grants and Contracts	Y
Procurement/Supply Services	Y
Research Property Managment	Y
Research Security Services	N
Reports Coordinator (OCA)	Y
GTRC	Y
Project File	Y
Other ____________________	N
____________________	N

NOTE: Final Patent Questionnaire sent to PDPI.

CERTIFICATE OF SERVICES/RESEARCH
CONTRACT NO. F33615-87-D-0626
GEORGIA TECH NO. B-10-A00/R6500

Period Covered: May 01, 1990 through May 31, 1990
Delivery Order No. 0013

I. DIRECT COSTS:

	Current	Cumulative
Personal Services	$ 0.00	$ 0.00
Fringe Benefits	0.00	0.00
Materials and Supplies	0.00	0.00
Equipment	0.00	0.00
Travel	0.00	0.00
Total Direct Costs	$ 0.00	$ 0.00
II. INDIRECT COSTS (62.5% of Direct Costs)	$ 0.00	$ 0.00
TOTAL	$ 0.00	$ 0.00

"I certify that the above is a true and correct statement of efforts performed under Contract No. F33615-87-D-0626 by the Georgia Institute of Technology through the Georgia Tech Research Corporation for the subject time period."

[redacted]

James C. Toler, Project Director

The above statement is approved for payment by the Government.

Richard Bixby

Cruz Cantu

Please forward approved "certificate" to:

Georgia Institute of Technology
Grants and Contracts Accounting
Attn: Sandi Chestnut
Atlanta, Georgia 30332-0259

CERTIFICATE OF SERVICES/RESEARCH
CONTRACT NO. F33615-87-D-0626
GEORGIA TECH NO. B-10-A00/R6500

Period Covered: June 01, 1990 through June 30, 1990
Delivery Order No. 0013

I. DIRECT COSTS:

	Current	Cumulative
Personal Services	$ 0.00	$ 0.00
Fringe Benefits	0.00	0.00
Materials and Supplies	0.00	0.00
Equipment	0.00	0.00
Travel	0.00	0.00
Total Direct Costs	$ 0.00	$ 0.00
II. INDIRECT COSTS (62.5% of Direct Costs)	$ 0.00	$ 0.00
TOTAL	$ 0.00	$ 0.00

"I certify that the above is a true and correct statement of efforts performed under Contract No. F33615-87-D-0626 by the Georgia Institute of Technology through the Georgia Tech Research Corporation for the subject time period."

[redacted]

James C. Toler, Project Director

The above statement is approved for payment by the Government.

Richard Bixby

Cruz Cantu

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Atlanta, Georgia 30332-0259

CERTIFICATE OF SERVICES/RESEARCH
CONTRACT NO. F33615-87-D-0626
GEORGIA TECH NO. B-03-A00/R6500

Period Covered: July 01, 1990 through July 31, 1990
Delivery Order No. 0013

I. DIRECT COSTS:

	Current	Cumulative
Personal Services	$ 6,133.33	$ 6,133.33
Fringe Benefits	1,613.07	1,613.07
Materials and Supplies	0.00	0.00
Equipment	0.00	0.00
Travel	0.00	0.00
Total Direct Costs	$ 7,746.40	$ 7,746.40
II. INDIRECT COSTS (62.5% of Direct Costs)	$ 4,841.50	$ 4,841.50
TOTAL	$ 12,587.90	$ 12,587.90

"I certify that the above is a true and correct statement of efforts performed under Contract No. F33615-87-D-0626 by the Georgia Institute of Technology through the Georgia Tech Research Corporation for the subject time period."

[redacted]

James C. Toler, Project Director

The above statement is approved for payment by the Government.

Richard Bixby

Cruz Cantu

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CERTIFICATE OF SERVICES/RESEARCH
CONTRACT NO. F33615-87-D-0626
GEORGIA TECH NO. B-03-A00/R6500

Period Covered: August 01, 1990 through August 31, 1990
Delivery Order No. 0013

I. DIRECT COSTS:

	Current	Cumulative
Personal Services	$ 6,133.33	$ 12,266.66
Fringe Benefits	1,613.07	3,226.14
Materials and Supplies	7.23	7.23
Equipment	0.00	0.00
Travel	0.00	0.00
Total Direct Costs	$ 7,753.63	$ 15,500.03
II. INDIRECT COSTS (62.5% of Direct Costs)	$ 4,846.02	$ 9,687.52
TOTAL	$ 12,599.65	$ 25,187.55

"I certify that the above is a true and correct statement of efforts performed under Contract No. F33615-87-D-0626 by the Georgia Institute of Technology through the Georgia Tech Research Corporation for the subject time period."

[redacted]

James C. Toler, Project Director

The above statement is approved for payment by the Government.

James H. Merritt

Cruz Cantu

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CERTIFICATE OF SERVICES/RESEARCH
CONTRACT NO. F33615-87-D-0626
GEORGIA TECH NO. B-03-A00/R6500

Period Covered: September 01, 1990 through September 30, 1990
Delivery Order No. 0013

I. DIRECT COSTS:

	Current	Cumulative
Personal Services	$ 6,133.33	$ 18,399.99
Fringe Benefits	1,613.07	4,839.21
Materials and Supplies	193.61	200.84
Equipment	0.00	0.00
Travel	792.84	792.84
Total Direct Costs	$ 8,732.85	$ 24,232.88

	Current	Cumulative
II. INDIRECT COSTS (62.5% of Direct Costs)	$ 5,458.03	$ 15,145.55
TOTAL	$ 14,190.88	$ 39,378.43

"I certify that the above is a true and correct statement of efforts performed under Contract No. F33615-87-D-0626 by the Georgia Institute of Technology through the Georgia Tech Research Corporation for the subject time period."

[redacted]

James C. Toler, Project Director

The above statement is approved for payment by the Government.

James H. Merritt

Cruz Cantu

Please forward approved "certificate" to:

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Atlanta, Georgia 30332-0259

Georgia Tech

Georgia Institute of Technology
Centennial Research Building
400 Tenth Street, N.W.
Atlanta, Georgia 30332-0130

BIOENGINEERING CENTER
404•894•3964
FAX: 404•894•3120

mes C. Toler, Director
pelectromagnetics Laboratory
-Director, Bioengineering Center
4) 894-3964

rberto F. Ezquerra, Director
dical Informatics Laboratory
4) 894-7026

ilip R. Kennedy, Director
uroscience Laboratory
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chael J. Sinclair, Director
potics and Microelectronics
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hael F. Burrow
) 894-7034

n W. Peifer
) 894-7028

sley W. Shelton, Jr.
) 894-8727

mas G. Single
) 894-7033

stal L. Tucker
894-7022

January 8, 1991

Mr. Jim Merritt
Code USAFSAM/RZP
Brooks AFB, TX 78235

Dear Mr. Merritt,

Please note that the attached Certificate of Services indicates a budget overage. This overage exists because only the first funding increment ($40,000) has been received. Upon receipt of the final funding increment ($85,000), project expenditures will again be in line with the available budget.

Sincerely,

[redacted]

J.C. Toler, Director
Project No. B-10-A13

CERTIFICATE OF SERVICES/RESEARCH
CONTRACT NO. F33615-87-D-0626
GEORGIA TECH NO. B-03-A00/R6500

Period Covered: October 01, 1990 through October 31, 1990
Delivery Order No. 0013

		Current		Cumulative
I. DIRECT COSTS:				
Personal Services	$	(369.41)	$	18,030.58
Fringe Benefits		(97.16)		4,742.05
Materials and Supplies		747.22		948.06
Equipment		0.00		0.00
Travel		1,540.00		2,332.84
Total Direct Costs	$	1,820.65	$	26,053.53
II. INDIRECT COSTS (62.5% of Direct Costs)	$	1,137.91	$	16,283.46
TOTAL	$	2,958.56	$	42,336.99

"I certify that the above is a true and correct statement of efforts performed under Contract No. F33615-87-D-0626 by the Georgia Institute of Technology through the Georgia Tech Research Corporation for the subject time period."

[redacted]

James C. Toler, Project Director

The above statement is approved for payment by the Government.

James H. Merritt

Cruz Cantu

Please forward approved "certificate" to:

Georgia Institute of Technology
Grants and Contracts Accounting
Attn: Sandi Chestnut
Atlanta, Georgia 30332-0259

CERTIFICATE OF SERVICES/RESEARCH
CONTRACT NO. F33615-87-D-0626
GEORGIA TECH NO. B-03-A00/R6500

Period Covered: November 01, 1990 through November 30, 1990
Delivery Order No. 0013

I. DIRECT COSTS:

		Current		Cumulative
Personal Services	$	0.00	$	18,030.58
Fringe Benefits		0.00		4,742.05
Materials and Supplies		0.00		948.06
Equipment		0.00		0.00
Travel		0.00		2,332.84
Total Direct Costs	$	0.00	$	26,053.53
II. INDIRECT COSTS (62.5% of Direct Costs)	$	0.00	$	16,283.46
TOTAL	$	0.00	$	42,336.99

"I certify that the above is a true and correct statement of efforts performed under Contract No. F33615-87-D-0626 by the Georgia Institute of Technology through the Georgia Tech Research Corporation for the subject time period."

[redacted]

James C. Toler, Project Director

The above statement is approved for payment by the Government.

James H. Merritt

Cruz Cantu

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Georgia Institute of Technology
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Atlanta, Georgia 30332-0259

CERTIFICATE OF SERVICES/RESEARCH
CONTRACT NO. F33615-87-D-0626
GEORGIA TECH NO. B-03-A00/R6500

Period Covered: December 01, 1990 through December 31, 1990
Delivery Order No. 0013

I. DIRECT COSTS:

		Current		Cumulative
Personal Services	$	9,800.00	$	27,830.58
Fringe Benefits		2,577.40		7,319.45
Materials and Supplies		0.00		948.06
Equipment		0.00		0.00
Travel		0.00		2,332.84
Total Direct Costs	$	12,377.40	$	38,430.93

II. INDIRECT COSTS

(62.5% of Direct Costs)	$	7,735.88	$	24,019.34
TOTAL	$	20,113.28	$	62,450.27

"I certify that the above is a true and correct statement of efforts performed under Contract No. F33615-87-D-0626 by the Georgia Institute of Technology through the Georgia Tech Research Corporation for the subject time period."

[redacted]

James C. Toler, Project Director

The above statement is approved for payment by the Government.

James H. Merritt

Cruz Cantu

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Georgia Institute of Technology
Grants and Contracts Accounting
Attn: Sandi Chestnut
Atlanta, Georgia 30332-0259

CERTIFICATE OF SERVICES/RESEARCH
CONTRACT NO. F33615-87-D-0626
GEORGIA TECH NO. B-03-A00/R6500

Period Covered: January 01, 1991 through January 31, 1991
Delivery Order No. 0013

I. DIRECT COSTS:

		Current		Cumulative
Personal Services	$	0.00	$	27,830.58
Fringe Benefits		0.00		7,319.45
Materials and Supplies		0.00		948.06
Equipment		0.00		0.00
Travel		0.00		2,332.84
Total Direct Costs	$	0.00	$	38,430.93
II. INDIRECT COSTS (62.5% of Direct Costs)	$	0.00	$	24,019.34
TOTAL	$	0.00	$	62,450.27

"I certify that the above is a true and correct statement of efforts performed under Contract No. F33615-87-D-0626 by the Georgia Institute of Technology through the Georgia Tech Research Corporation for the subject time period."

[redacted]

James C. Toler, Project Director

The above statement is approved for payment by the Government.

James H. Merritt

Cruz Cantu

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CERTIFICATE OF SERVICES/RESEARCH
CONTRACT NO. F33615-87-D-0626
GEORGIA TECH NO. B-03-A00/R6500

Period Covered: February 01, 1991 through February 28, 1991
Delivery Order No. 0013

I. DIRECT COSTS:

	Current	Cumulative
Personal Services	$ 19,024.38	$ 46,854.96
Fringe Benefits	5,003.41	12,322.86
Materials and Supplies	0.00	948.06
Equipment	0.00	0.00
Travel	989.80	3,322.64
Total Direct Costs	$ 25,017.59	$ 63,448.52

II. INDIRECT COSTS

(62.5% of Direct Costs)	$ 15,635.99	$ 39,655.33
TOTAL	$ 40,653.58	$ 103,103.85

"I certify that the above is a true and correct statement of efforts performed under Contract No. F33615-87-D-0626 by the Georgia Institute of Technology through the Georgia Tech Research Corporation for the subject time period."

[redacted]

James C. Toler, Project Director

The above statement is approved for payment by the Government.

James H. Merritt

Cruz Cantu

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Georgia Institute of Technology
Grants and Contracts Accounting
Attn: Sandi Chestnut
Atlanta, Georgia 30332-0259

CERTIFICATE OF SERVICES/RESEARCH
CONTRACT NO. F33615-87-D-0626
GEORGIA TECH NO. B-03-A00/R6500

Period Covered: March 01, 1991 through March 31, 1991
Delivery Order No. 0013

		Current		Cumulative
I. DIRECT COSTS:				
Personal Services	$	5,800.00	$	52,654.96
Fringe Benefits		1,525.40		13,848.26
Materials and Supplies		0.00		948.06
Equipment		0.00		0.00
Travel		0.00		3,322.64
Total Direct Costs	$	7,325.40	$	70,773.92
II. INDIRECT COSTS (62.5% of Direct Costs)	$	4,578.38	$	44,233.70
TOTAL	$	11,903.78	$	115,007.62

"I certify that the above is a true and correct statement of efforts performed under Contract No. F33615-87-D-0626 by the Georgia Institute of Technology through the Georgia Tech Research Corporation for the subject time period."

[redacted]

James C. Toler, Project Director

The above statement is approved for payment by the Government.

James H. Merritt

Cruz Cantu

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Georgia Institute of Technology
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Atlanta, Georgia 30332-0259

Georgia Tech

Georgia Institute of Technology
Centennial Research Building
400 Tenth Street, N.W.
Atlanta, Georgia 30332-0130

BIOENGINEERING CENTER
404•894•3964
FAX: 404•894•3120

10 July 1990

Department of the Air Force
Air Force Systems Command
Aeronautical Systems Division/PMRSC
Wright-Patterson AFB, OH 4533-6503

James C. Toler, Director
Bioelectromagnetics Laboratory
Co-Director, Bioengineering Center
(404) 894-3964

Norberto F. Ezquerra, Director
Medical Informatics Laboratory
(404) 894-7026

Philip R. Kennedy, Director
Neuroscience Laboratory
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Michael J. Sinclair, Director
Robotics and Microelectronics Laboratory
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KEY STAFF

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John W. Peifer
(404) 894-7028

Wesley W. Shelton, Jr.
(404) 894-8727

Thomas G. Single
(404) 894-7033

Crystal L. Tucker
(404) 894-7022

Contract No.: F33615-87-D-0626
Item No.: 0001 Sequence No.: 13

Reference: Contract No. F33615-87-D-0626, Delivery Order 0013, "Development of High Power Microwave Devices for Use in Bioeffects Studies," Georgia Tech Project No. B-10-A13

Subject: Performance and Cost Report No. 1
Reporting Period: 2 May 1990 to 31 May 1990

Gentlemen:

This Delivery Order specifies an engineering study which will culminate in recommendations in equipment designs and configurations that might best simulate field parameters likely to be encountered in high power microwave research and operations. In formulating design recommendations, considerations are to include the use of conventional as well as novel sources, single and multiple antennas (phased arrays), conformal arrays, and other such designs as may be considered practicable in the present state-of-the-art. A written report of recommendations, including suggested designs and configurations at the block diagram and/or conceptual drawing level of detail, will be delivered at the end of the study period.

I. PERFORMANCE REPORT

The award date for this Delivery Order is 2 May 1990, and the initial funding increment is $40,000. The total approved funding is $125,508.

Administrative processing of this award was not completed until the last week in May 1990, and only the formulation of plans to accomplish task objectives was performed.

II. COST REPORT

No costs for this project were charged against this contract for May 1990.

Respectfully submitted,

[redacted]

W. W. Shelton, Jr.
Project Director

Approved

[redacted]

J.C Toler, Co-Director
Bioengineering Center

cc: Mr. James H. Merritt, USAFSAM/RZP

Georgia Tech

Georgia Institute of Technology
Centennial Research Building
400 Tenth Street, N.W.
Atlanta, Georgia 30332-0130

BIOENGINEERING CENTER
404•894•3964
FAX: 404•894•3120

10 July 1990

Department of the Air Force
Air Force Systems Command
Aeronautical Systems Division/PMRSC
Wright-Patterson AFB, OH 4533-6503

Contract No.: F33615-87-D-0626
Item No.: 0001 Sequence No.: 13

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Bioelectromagnetics Laboratory
Co-Director, Bioengineering Center
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(404) 894-7022

Reference: Contract No. F33615-87-D-0626, Delivery Order 0013, "Development of High Power Microwave Devices for Use in Bioeffects Studies," Georgia Tech Project No. B-10-A13

Subject: Performance and Cost Report No. 2 Reporting Period: 1 June 1990 to 30 June 1990

Gentlemen:

This Delivery Order specifies an engineering study which will culminate in recommendations in equipment designs and configurations that might best simulate field parameters likely to be encountered in high power microwave research and operations. In formulating design recommendations, considerations are to include the use of conventional as well as novel sources, single and multiple antennas (phased arrays), conformal arrays, and other such de-signs as may be considered practicable in the present state-of-the-art. A written report of recommendations, including suggested designs and configurations at the block diagram and/or conceptual drawing level of detail, will be delivered at the end of the study period.

I. PERFORMANCE REPORT

This month was used primarily to gather technical documents, books, journals and other resources to support the project. A visit with the Government Technical Point of Contact was made during attendance at the June 1990 Annual Meeting of the Bioelectromagnetics Society in San Antonio, Texas. A number of technical reprints on the bioelectromagnetic aspects of pulsed, high-power microwave and millimeter wave energy have been reviewed and information on pertinent power sources and radiating apertures and structures has been acquired and studied.

II. COST REPORT

End-of-the-fiscal-year "closing-out" activities of accounting have delayed the print out of project charges normally available by the time Performance and Cost Reports are prepared, and therefore that information is omitted from this report. Next month's report will include that information in the "Cumulative Costs" section.

Respectfully submitted,

[redacted]

W. W. Shelton, Jr.
Project Director

Approved

[redacted]

J.C Toler, Co-Director
Bioengineering Center

cc: Mr. James H. Merritt, USAFSAM/RZP

Georgia Tech

Georgia Institute of Technology
Centennial Research Building
400 Tenth Street, N.W.
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BIOENGINEERING CENTER
404•894•3964
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12 August 1990

Department of the Air Force
Air Force Systems Command
Aeronautical Systems Division/PMRSC
Wright-Patterson AFB, OH 4533-6503

Contract No.: F33615-87-D-0626
Item No.: 0001 Sequence No.: 13

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Thomas G. Single
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Crystal L. Tucker
(404) 894-7022

Reference: Contract No. F33615-87-D-0626, Delivery Order 0013, "Development of High Power Microwave Devices for Use in Bioeffects Studies," Georgia Tech Project No. B-10-A13

Subject: Performance and Cost Report No. 3
Reporting Period: 1 June 1990 to 30 June 1990

Gentlemen:

This Delivery Order specifies an engineering study which will culminate in recommendations in equipment designs and configurations that might best simulate field parameters likely to be encountered in high power microwave research and operations. In formulating design recommendations, considerations are to include the use of conventional as well as novel sources, single and multiple antennas (phased arrays), conformal arrays, and other such designs as may be considered practicable in the present state-of-the-art. A written report of recommendations, including suggested designs and configurations at the block diagram and/or conceptual drawing level of detail, will be delivered at the end of the study period.

I. PERFORMANCE REPORT

This month was involved the continuation of resource gathering and the analysis of materials gathered thus far.

II. COST REPORT

June is the "close out" month for the fiscal year at Georgia Tech. Because of this, project budget sheets for June are often late in reflecting costs incurred during this month. That was the case for this project, making it necessary for Performance and Cost Report No. 4 to reflect costs incurred for both June and July 1990.

Costs incurred during the June 1990 period were:

Personnel Services	$00,000.00
Fringe Benefits	$00,000.00
Materials and Supplies	$00,000.00
Travel	$00,000.00
Equipment	$00,000.00
Overhead	$00,000.00
TOTAL:	$00,000.00

Cumulative costs incurred through June 1990 were:

Personal Services	$00,000.00
Fringe Benefits	$00,000.00
Materials and Supplies	$00,000.00
Travel	$00,000.00
Equipment	$00,000.00
Overhead	$00,000.00
TOTAL:	$00,000.00

Respectfully submitted,

[redacted]

Wesley W. Shelton, Jr.
Project Director

Approved

[redacted]

J.C. Toler, Co-Director
Bioengineering Center

cc: Mr. James H. Merritt, USAFSAM/RZP

Georgia Tech

Georgia Institute of Technology
Centennial Research Building
400 Tenth Street, N.W.
Atlanta, Georgia 30332-0130

BIOENGINEERING CENTER
404•894•3964
FAX: 404•894•3120

2 October 1990

Department of the Air Force
Air Force Systems Command
Aeronautical Systems Division/PMRSC
Wright-Patterson AFB, OH 4533-6503

Contract No.: F33615-87-D-0626
Item No.: 0001 Sequence No.: 13

James C. Toler, Director
Bioelectromagnetics Laboratory
Co-Director, Bioengineering Center
(404) 894-3964

Norberto F. Ezquerra, Director
Medical Informatics Laboratory
(404) 894-7026

Philip R. Kennedy, Director
Neuroscience Laboratory
(404) 894-4257

Michael J. Sinclair, Director
Robotics and Microelectronics Laboratory
(404) 894-4931

KEY STAFF

David M. Banks
(404) 894-7020

Stephen J. Bonasera
(404) 894-7031

Michael F. Burrow
(404) 894-7034

John W. Peifer
(404) 894-7028

Wesley W. Shelton, Jr.
(404) 894-8727

Thomas G. Single
(404) 894-7033

Crystal L. Tucker
(404) 894-7022

Reference: Contract No. F33615-87-D-0626, Delivery Order 0013, "Development of High Power Microwave Devices for Use in Bioeffects Studies," Georgia Tech Project No. B-10-A13

Subject: Performance and Cost Report No. 4
Reporting Period: 1 July 1990 to 31 July 1990

Gentlemen:

This Delivery Order specifies an engineering study which will culminate in recommendations in equipment designs and configurations that might best simulate field parameters likely to be encountered in high power microwave research and operations. In formulating design recommendations, considerations are to include the use of conventional as well as novel sources, single and multiple antennas (phased arrays), conformal arrays, and other such de-signs as may be considered practicable in the present state-of-the-art. A written report of recommendations, including suggested designs and configurations at the block diagram and/or conceptual drawing level of detail, will be delivered at the end of the study period.

I. PERFORMANCE REPORT

This month's work continued the process of resource gathering and the analysis of those resource materials with regard to compatibility of performance features with the design requirements for the bioeffects simulation environment and cost effectiveness. Development of software was also begun.

II. COST REPORT

End-of-the-fiscal-year "closing-out" activities of accounting preclude the print out of project charges normally available by the time Performance and Cost Reports were prepared last reporting period, and, as noted in the last report, that information was therefore omitted from that report. This report incorporates that information in the "Cumulative Costs" section.

Costs incurred during the June 1990 period were:

Personnel Services	$ 6,133.33
Fringe Benefits	$ 1,613.07
Materials and Supplies	$00,000.00
Travel	$00,000.00
Equipment	$00,000.00
Overhead	$ 4,841.50
TOTAL:	$12,587.90

Cumulative costs incurred through June 1990 were:

Personal Services	$ 6,133.33
Fringe Benefits	$ 1,613.07
Materials and Supplies	$00,000.00
Travel	$00,000.00
Equipment	$00,000.00
Overhead	$ 4,841.50
TOTAL:	$12,587.90

Respectfully submitted,

[redacted]

Wesley W. Shelton, Jr.
Project Director

Approved

[redacted]

J.C. Toler, Co-Director
Bioengineering Center

cc: Mr. James H. Merritt, USAFSAM/RZP

Georgia Tech

Georgia Institute of Technology
Centennial Research Building
400 Tenth Street, N.W.
Atlanta, Georgia 30332-0130

BIOENGINEERING CENTER
404•894•3964
FAX: 404•894•3120

2 October 1990

Department of the Air Force
Air Force Systems Command
Aeronautical Systems Division/PMRSC
Wright-Patterson AFB, OH 4533-6503

Contract No.: F33615-87-D-0626-0013
Item No.: 0001 Sequence No.: 1

Reference: Contract No. F33615-87-D-0626, Delivery Order 0013,"Development of High Power Microwave Devices for Use in Bioeffects Studies," Georgia Tech Project No. B-03-A13

Subject: Performance & Cost - Cumulative
Reporting Period: 2 May 1990 to 31 July 1990

James C. Toler, Director
Bioelectromagnetics Laboratory
Co-Director, Bioengineering Center
(404) 894-3964

Norberto F. Ezquerra, Director
Medical Informatics Laboratory
(404) 894-7026

Philip R. Kennedy, Director
Neuroscience Laboratory
(404) 894-4257

Michael J. Sinclair, Director
Robotics and Microelectronics Laboratory
(404) 894-4931

KEY STAFF

David M. Banks
(404) 894-7020

Stephen J. Bonasera
(404) 894-7031

Michael F. Burrow
(404) 894-7034

John W. Peifer
(404) 894-7028

Wesley W. Shelton, Jr.
(404) 894-8727

Thomas G. Single
(404) 894-7033

Crystal L. Tucker
(404) 894-7022

Gentlemen:

This Delivery Order specifies an engineering study which will culminate in recommendations in equipment designs and configurations that might best simulate field parameters likely to be encountered in high power microwave research and operations. In formulating design recommendations, considerations are to include the use of conventional as well as novel sources, single and multiple antennas (phased arrays), conformal arrays, and other such designs as may be considered practicable in the present state-of-the-art. A written report of recommendations, including suggested designs and configurations at the block diagram and/or conceptual drawing level of detail, will be delivered at the end of the study period.

I. PERFORMANCE REPORT-CUMULATIVE

During this cumulative reporting period, efforts were concentrated on the acquisition of the technical literature pertaining to power sources and antenna systems that might be used in the simulation designs specified for this study. Analysis of performance capabilities (e.g., output power, pulse-width, PRF) for candidate devices and cost comparisons was begun. The development of software to assist in the simulation design was also begun.

II. COST REPORT

Cumulative costs incurred through July 1990 were:

Personnel Services	$ 6,133.33
Fringe Benefits	$ 1,613.07
Materials and Supplies	$00,000.00
Travel	$00,000.00
Equipment	$00,000.00
Overhead	$ 4,841.50
TOTAL:	$12,587.90

Respectfully submitted,

[redacted]

Wesley W. Shelton, Jr.
Project Director

Approved

[redacted]

J.C. Toler, Co-Director
Bioengineering Center

cc: Mr. James H. Merritt, USAFSAM/RZP

Georgia Tech

Georgia Institute of Technology
Centennial Research Building
400 Tenth Street, N.W.
Atlanta, Georgia 30332-0130

BIOENGINEERING CENTER
404•894•3964
FAX: 404•894•3120

2 October 1990

Department of the Air Force
Air Force Systems Command
Aeronautical Systems Division/PMRSC
Wright-Patterson AFB, OH 4533-6503

Contract No.: F33615-87-D-0626
Item No.: 0001 Sequence No.: 13

James C. Toler, Director
Bioelectromagnetics Laboratory
Co-Director, Bioengineering Center
(404) 894-3964

Norberto F. Ezquerra, Director
Medical Informatics Laboratory
(404) 894-7026

Philip R. Kennedy, Director
Neuroscience Laboratory
(404) 894-4257

Michael J. Sinclair, Director
Robotics and Microelectronics Laboratory
(404) 894-4931

KEY STAFF

David M. Banks
(404) 894-7020

Stephen J. Bonasera
(404) 894-7031

Michael F. Burrow
(404) 894-7034

John W. Peifer
(404) 894-7028

Wesley W. Shelton, Jr.
(404) 894-8727

Thomas G. Single
(404) 894-7033

Crystal L. Tucker
(404) 894-7022

Reference: Contract No. F33615-87-D-0626, Delivery Order 0013, "Development of High Power Microwave Devices for Use in Bioeffects Studies," Georgia Tech Project No. B-10-A13

Subject: Performance and Cost Report No. 5
Reporting Period: 1 August 1990 to 31 August 1990

Gentlemen:

This Delivery Order specifies an engineering study which will culminate in recommendations in equipment designs and configurations that might best simulate field parameters likely to be encountered in high power microwave research and operations. In formulating design recommendations, considerations are to include the use of conventional as well as novel sources, single and multiple antennas (phased arrays), conformal arrays, and other such designs as may be considered practicable in the present state-of-the-art. A written report of recommendations, including suggested designs and configurations at the block diagram and/or conceptual drawing level of detail, will be delivered at the end of the study period.

I. PERFORMANCE REPORT

This month's effort was directed primarily to the review of several devices potentially useful for the generation of high power microwave signals needed for the simulations specified for this contract. High-power klystrons and travelling-wave tubes were the focus this month, and assessment of their respective capabilities (output power, operating frequencies, bandwidth, pulse widths, PRFs, pulse-to-pulse stability, reliability, cost, etc.) was begun. Their performance parameters were used in the preliminary software developed last month to further explore their potential usefulness in the simulation designs.

II. COST REPORT

Costs incurred during the August 1990 period were:

Personnel Services	\$ 6,133.33
Fringe Benefits	\$ 1,613.07
Materials and Supplies	\$ 7.23
Travel	\$00,000.00
Equipment	\$00,000.00
Overhead	\$ 4,846.02
TOTAL:	\$12,599.65

Cumulative costs incurred through August 1990 were:

Personal Services	$12,266.66
Fringe Benefits	$ 3,226.14
Materials and Supplies	$ 7.23
Travel	$00,000.00
Equipment	$00,000.00
Overhead	$ 9,687.52
TOTAL:	$25,187.55

Respectfully submitted,

[redacted]

Wesley W. Shelton, Jr.
Project Director

Approved

[redacted]

J.C. Toler, Co-Director
Bioengineering Center

cc: Mr. James H. Merritt, USAFSAM/RZP

Georgia Tech

Georgia Institute of Technology
Centennial Research Building
400 Tenth Street, N.W.
Atlanta, Georgia 30332-0130

BIOENGINEERING CENTER
404•894•3964
FAX: 404•894•3120

James C. Toler, Director
Bioelectromagnetics Laboratory
Co-Director, Bioengineering Center
(404) 894-3964

Norberto F. Ezquerra, Director
Medical Informatics Laboratory
(404) 894-7026

Philip R. Kennedy, Director
Neuroscience Laboratory
(404) 894-4257

Michael J. Sinclair, Director
Robotics and Microelectronics Laboratory
(404) 894-4931

KEY STAFF

David M. Banks
(404) 894-7020

Stephen J. Bonasera
(404) 894-7031

Michael F. Burrow
(404) 894-7034

John W. Peifer
(404) 894-7028

Wesley W. Shelton, Jr.
(404) 894-8727

Thomas G. Single
(404) 894-7033

Crystal L. Tucker
(404) 894-7022

5 November 1990

Department of the Air Force
Air Force Systems Command
Aeronautical Systems Division/PMRSC
Wright-Patterson AFB, OH 4533-6503

Contract No.: F33615-87-D-0626
Item No.: 0001 Sequence No.: 13

Reference: Contract No. F33615-87-D-0626, Delivery Order 0013, "Development of High Power Microwave Devices for Use in Bioeffects Studies," Georgia Tech Project No. B-10-A13

Subject: Performance and Cost Report No. 6
Reporting Period: 1 September 1990 to 30 September 1990

Gentlemen:

This Delivery Order specifies an engineering study which will culminate in recommendations in equipment designs and configurations that might best simulate field parameters likely to be encountered in high power microwave research and operations. In formulating design recommendations, considerations are to include the use of conventional as well as novel sources, single and multiple antennas (phased arrays), conformal arrays, and other such designs as may be considered practicable in the present state-of-the-art. A written report of recommendations, including suggested designs and configurations at the block diagram and/or conceptual drawing level of detail, will be de- livered at the end of the study period.

I. PERFORMANCE REPORT

This month's effort was directed primarily to the review of several devices potentially useful for the generation of high power microwave signals needed for the simulations specified for this contract. Magnetrons and twystron amplifier specifications were reviewed and evaluated this month along with the devices described in last month's report. Peak and average output power, operating frequencies, bandwidth, pulse widths, PRFs, pulse-to-pulse stability, and reliability were the operating parameters of interest. Their performance parameters were used in the preliminary software developed in August to assist in evaluating their potential usefulness in the simulation designs.

Interest has converged to those sources which are identified as being capable of generating peak powers at the megawatt level. Several devices have been selected for further analysis and, as other (requested) information arrives, additional devices will be added to the list of promising candidates.

The nominal operating characteristics of Varian pulsed, high-power amplifiers (as specified by the manufacturer) are given here:

Varian	VA-963A	VKL-7796	VKS-8262B	VA-145UH	VA-146C
Tube type (*).	K	K	K	T	T
Peak output power (MW)....	5.0	4.0	5.0	3.0	3.2
Ave. output power (kW)....	10	300	5	8.5	10
Freq. band....	L	L	S	S	C
Duty cycle....	0.002	0.075	0.001	0.0025	0.002
Pulse width (microsec.)...	3	130	5	10	12.5

* K=Klystron T=Twystron

Other considerations such as system losses, antenna gain and beam-width, weight and size restrictions, simplicity of design, cost, etc., will strongly influence the selection of the high-power device or combination of devices for the specific radiation simulations. Ideally, a single high-power device will be found for each simulation case.

A more comprehensive tabulation will be submitted with next month's report.

II. COST REPORT

Costs incurred during the September 1990 period were:

Personnel Services	$ 6,133.33
Fringe Benefits	$ 1,613.07
Materials and Supplies	$ 193.61
Travel	$ 792.84
Equipment	$ 0.00
Overhead	$ 5,458.03
TOTAL:	$14,190.88

Cumulative costs incurred through September 1990 were:

Personal Services	$18,399.99
Fringe Benefits	$ 4,839.21
Materials and Supplies	$ 200.84
Travel	$ 792.84
Equipment	$ 0.00
Overhead	$15,145.55
TOTAL:	$39,378.43

Respectfully submitted,

[redacted]

Wesley W. Shelton, Jr.
Project Director

Approved

[redacted]

J.C. Toler, Co-Director
Bioengineering Center

cc: Mr. James H. Merritt, USAFSAM/RZP

Georgia Tech

Georgia Institute of Technology
Centennial Research Building
400 Tenth Street, N.W.
Atlanta, Georgia 30332-0130

BIOENGINEERING CENTER
404•894•3964
FAX: 404•894•3120

4 December 1990

Department of the Air Force
Air Force Systems Command
Aeronautical Systems Division/PMRSC
Wright-Patterson AFB, OH 4533-6503

Contract No.: F33615-87-D-6503
Item No.: 0001 Sequence No.:13

James C. Toler, Director
Bioelectromagnetics Laboratory
Co-Director, Bioengineering Center
(404) 894-3964

Norberto F. Ezquerra, Director
Medical Informatics Laboratory
(404) 894-7026

Philip R. Kennedy, Director
Neuroscience Laboratory
(404) 894-4257

Michael J. Sinclair, Director
Robotics and Microelectronics Laboratory
(404) 894-4931

KEY STAFF

David M. Banks
(404) 894-7020

Stephen J. Bonasera
(404) 894-7031

Michael F. Burrow
(404) 894-7034

John W. Peifer
(404) 894-7028

Wesley W. Shelton, Jr.
(404) 894-8727

Thomas G. Single
(404) 894-7033

Crystal L. Tucker
(404) 894-7022

Reference: Contract No. F33615-87-D-0626, Delivery Order 0013, "Development of High Power Microwave Devices for Use in Bioeffects Studies," Georgia Tech Project No. B-10-A13

Subject: Performance and Cost Report No. 7
Reporting Period: 1 October 1990 to 31 October 1990

Gentlemen:

This Delivery Order specifies an engineering study which will culminate in recommendations in equipment designs and configurations that might best simulate field parameters likely to be encountered in high power microwave research and operations. In formulating design recommendations, considerations are to include the use of conventional as well as novel sources, single and multiple antennas (phased arrays), conformal arrays, and other such designs as may be considered practicable in the present state-of-the-art. A written report of recommendations, including suggested designs and configurations at the block diagram and/or conceptual drawing level of detail, will be delivered at the end of the study period.

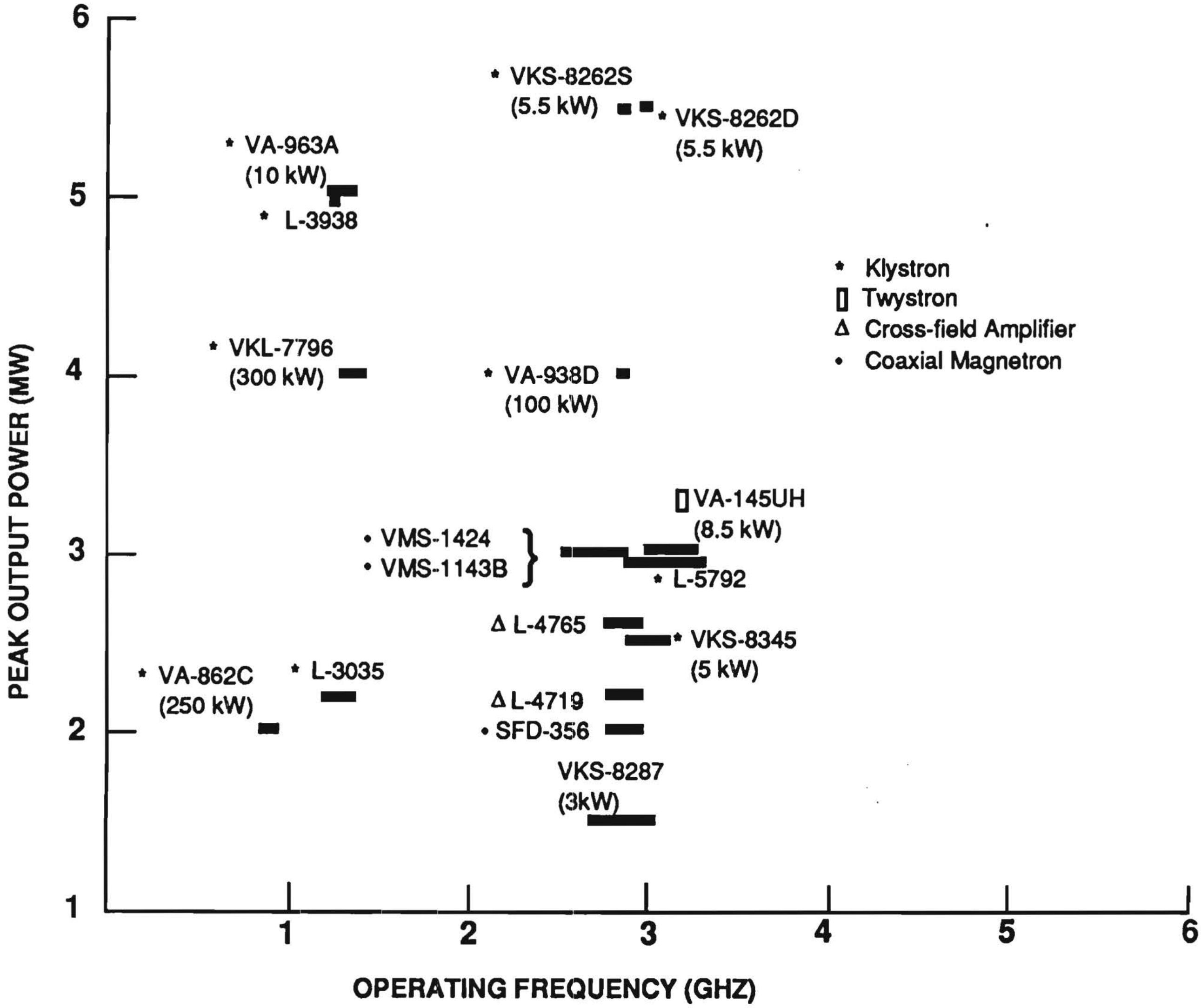
I. PERFORMANCE REPORT

During this reporting period work was focussed primarily on reviewing recently acquired technical materials on microwave transmission devices and identifying those which appeared to be compatible with the high-power microwave design goals of this project. The most current technical information on transmitters was recieved from Varian, Litton, EEV, Hughes, and M/A-COM, and brief discussions were held with several technical representatives. Additionally, time was allocated to study possible microwave lens approaches to increasing output power densities. Metal and dielectric lenses were considered in these preliminary studies.

This report features 18 transmitters, selected from the technical literature, which are specified as operating in the upper UHF (0.928 GHz), L, and S (3.3 GHz) frequency bands (or, using the new designations, the upper C-band through the lower F-band) and producing peak output powers on the order of 1.5 MW to 5.5 MW. Transmitters capable of higher peak power operation as well as operation in other frequency ranges wil be presented in next month's report.

HPM Table 1 tabulates the 18 transmitters along with important operating parameters specified by the manufacturers. HPM Figure 1 plots the peak output powers of these transmitters vs the frequency ranges over which they are specified to operate. On the plot, the transmitters are identified by model number, transmitter (tube) type, and by the average output power (in parentheses) whenever this parameter is given by the manufacturer.

The information presented for these devices is just for single device operations. The feasibility of amplifier chains of, e.g., the Litton S-band cross-field amplifier L-4719, to achieve even higher peak powers (in excess of 3 MW for the L-4719) remains to be addressed. Additionally, manufacturers have indicated the



HPM Figure 1. Peak output powers of several microwave transmitters plotted against frequency ranges of operation as specified by the respective manufacturers. Average output powers are given in parentheses wherever specified by the manufacturers.

HPM Table 1

Company	Model	Peak Output Power (MW)	Ave. Output Power (kW)	Operating Freq. (GHz)	Duty Cycle	Pulse Width (μsec)	Weight (Lb.)	Length (In.)	Tube Type
Varian									
	VMS-1424	3	-	2.7-2.9	-	-	-	-	Coax Magnetron
	VMS-1143B	3	-	2.7-2.9	-	-	-	-	Coax Magnetron
	SFD-356	2	-	2.85-2.91	-	-	-	-	Coax Magnetron
	SFD-356D	2	-	2.85-2.91	-	-	-	-	Coax Magnetron
	VA-862C	2	250	0.928-0.938	0.125	10000	800	110	Klystron
	VKL-7796	4	300	1.29-1.36	0.075	130	600	95	Klystron
	VA-963A	5	10	1.25-1.35	0.002	3	150	60	Klystron
	VKS-8287	1.5	3	2.7-3.0	0.002	6	90	38	Klystron
	VA-938D	4	100	2.856	0.025	20	580	64	Klystron
	VKS-8345	2.5	5	2.9-3.1	0.002	7	140	43	Klystron
	VKS-8262S	5.5	5.5	2.865	0.001	5	100	35	Klystron
	VKS-8262	5.5	5.5	2.999	0.001	5	150	40	Klystron
	VA-145UH	3	8.5	3.015-3.215	0.0025	10	140	42	Twystron
Litton									
	L-3035	2.2	-	1.24-1.36	0.003	-	-	-	Klystron
	L-3938	5	-	1.3	0.03	-	-	-	Klystron
	L-4719	2.2	-	2.9-3.1	0.0125	28	-	-	Cross-field Amp.
	L-4765	2.6	-	2.9-3.1	0.0053	28	-	-	Cross-field Amp.
	L-5792	3	-	2.9-3.3	0.002	-	-	-	Klystron

amplifier L-4719, to achieve even higher peak powers (in excess of 3 MW for the L-4719) remains to be addressed. Additionally, manufacturers have indicated the existence of other devices which are not listed, but which might become available; discussions with representatives will be held regarding these (probably very expensive) devices should listed devices prove inadequate.

II. COST REPORT

Costs incurred during the October 1990 period were:

Personal Services	$ -369.41
Fringe Benefits	$ -97.16
Materials and Supplies	$ 747.22
Travel	$ 1,540.00
Computer	$ 0.00
Overhead	$ 1,137.91
TOTAL	$ 2,958.56

Cumulative costs incurred through October 1990 were:

Personal Services	$18,030.58
Fringe Benefits	$ 4,742.05
Materials and Supplies	$ 948.06
Travel	$ 2,332.84
Computer	$ 0.00
Overhead	$16,283.46
TOTAL	$42,336.99

Respecfully submitted,

[redacted]

Wesley W. Shelton, Jr.
Projector Director

Approved [redacted]

J.C. Toler, Co-director
Bioengineering Center

cc: Mr. James H. Merritt, USAFSAM/RZP

Georgia Tech

Georgia Institute of Technology
Centennial Research Building
400 Tenth Street, N.W.
Atlanta, Georgia 30332-0130

BIOENGINEERING CENTER
404•894•3964
FAX: 404•894•3120

10 December 1990

Department of the Air Force
Air Force Systems Command
Aeronautical Systems Division/PMRSC
Wright-Patterson AFB, OH 4533-6503

Contract No.: F33615-87-D-6503
Item No.: 0001 Sequence No.:1

James C. Toler, Director
Bioelectromagnetics Laboratory
Co-Director, Bioengineering Center
(404) 894-3964

Norberto F. Ezquerra, Director
Medical Informatics Laboratory
(404) 894-7026

Philip R. Kennedy, Director
Neuroscience Laboratory
(404) 894-4257

Michael J. Sinclair, Director
Robotics and Microelectronics Laboratory
(404) 894-4931

KEY STAFF

David M. Banks
(404) 894-7020

Stephen J. Bonasera
(404) 894-7031

Michael F. Burrow
(404) 894-7034

John W. Peifer
(404) 894-7028

Wesley W. Shelton, Jr.
(404) 894-8727

Thomas G. Single
(404) 894-7033

Crystal L. Tucker
(404) 894-7022

Reference: Contract No. F33615-87-D-0626, Delivery Order 0013, "Development of High Power Microwave Devices for Use in Bioeffects Studies," Georgia Tech Project No. B-10-A13

Subject: R&D Status Report-Cumulative
Reporting Period: 1 August 1990 to 31 October 1990

Gentlemen:

This Delivery Order specifies an engineering study which will culminate in recommendations in equipment designs and configurations that might best simulate field parameters likely to be encountered in high power microwave research and operations. In formulating design recommendations, considerations are to include the use of conventional as well as novel sources, single and multiple antennas (phased arrays), conformal arrays, and other such designs as may be considered practicable in the present state-of-the-art. A written report of recommendations, including suggested designs and configurations at the block diagram and/or conceptual drawing level of detail, will be delivered at the end of the study period.

I. PERFORMANCE REPORT-CUMULATIVE

During this cumulative reporting period work was focussed primarily on acquiring and analyzing technical materials on microwave transmission devices and identifying those which appeared to be compatible with the high-power microwave design goals of this project. Up-to-date technical information on transmitters was received from Varian, Litton, EEV, Hughes, and M/A-COM, and informal technical discussions were held with several technical representatives. Additionally, time was spent on the study of possible microwave lens approaches to increasing output power densities. Metal and dielectric lenses were considered in these preliminary studies.

Performance data on 18 transmitters, selected from the technical literature, which operated in the upper UHF (0.928 GHz), L, and S (3.3 GHz) frequency bands (or, using the new designations, the upper C-band through the lower F-band) and produced peak output powers on the order of 1.5 MW to 5.5 MW were submitted in table and graph formats for consideration. Transmitters capable of higher peak power operation as well as operation in other frequency ranges were also identified as likely candidates and their operating parameters were being prepared for submittal.

Respecfully submitted,

[redacted]

Wesley W. Shelton, Jr.
Projector Director

Approved

[redacted]

J.C. Toler, Co-director
Bioengineering Center

cc: Mr. James H. Merritt, USAFSAM/RZP

Georgia Tech

Georgia Institute of Technology
Centennial Research Building
400 Tenth Street, N.W.
Atlanta, Georgia 30332-0130

BIOENGINEERING CENTER
404•894•3964
FAX: 404•894•3120

10 December 1990

Department of the Air Force
Air Force Systems Command
Aeronautical Systems Division/PMRSC
Wright-Patterson AFB, OH 4533-6503

Contract No.: F33615-87-D-6503
Item No.: 0001 Sequence No.:14

James C. Toler, Director
Bioelectromagnetics Laboratory
Co-Director, Bioengineering Center
(404) 894-3964

Norberto F. Ezquerra, Director
Medical Informatics Laboratory
(404) 894-7026

Philip R. Kennedy, Director
Neuroscience Laboratory
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Robotics and Microelectronics Laboratory
(404) 894-4931

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(404) 894-8727

Thomas G. Single
(404) 894-7033

Crystal L. Tucker
(404) 894-7022

Reference: Contract No. F33615-87-D-0626, Delivery Order 0013, "Development of High Power Microwave Devices for Use in Bioeffects Studies," Georgia Tech Project No. B-10-A13

Subject: Cumulative Performance and Cost Report Reporting Period: 1 August 1990 to 31 October 1990

Gentlemen:

This Delivery Order specifies an engineering study which will culminate in recommendations in equipment designs and configurations that might best simulate field parameters likely to be encountered in high power microwave research and operations. In formulating design recommendations, considerations are to include the use of conventional as well as novel sources, single and multiple antennas (phased arrays), conformal arrays, and other such designs as may be considered practicable in the present state-of-the-art. A written report of recommendations, including suggested designs and configurations at the block diagram and/or conceptual drawing level of detail, will be delivered at the end of the study period.

I. PERFORMANCE REPORT-CUMULATIVE

During this cumulative reporting period work was focussed primarily on acquiring and analyzing technical materials on microwave transmission devices and identifying those which appeared to be compatible with the high-power microwave design goals of this project. Up-to-date technical information on transmitters was received from Varian, Litton, EEV, Hughes, and M/A-COM, and informal technical discussions were held with several technical representatives. Additionally, time was spent on the study of possible microwave lens approaches to increasing output power densities. Metal and dielectric lenses were considered in these preliminary studies.

Performance data on 18 transmitters, selected from the technical literature, which operated in the upper UHF (0.928 GHz), L, and S (3.3 GHz) frequency bands (or, using the new designations, the upper C-band through the lower F-band) and produced peak output powers on the order of 1.5 MW to 5.5 MW were submitted in table and graph formats for consideration. Transmitters capable of higher peak power operation as well as operation in other frequency ranges were also identified as likely candidates and their operating parameters were being prepared for submittal.

II. CUMULATIVE COST REPORT

Cumulative costs incurred through October 1990 were:

Personal Services	$18,030.58
Fringe Benefits	$ 4,742.05
Materials and Supplies	$ 948.06
Travel	$ 2,332.84
Computer	$ 0.00
Overhead	$16,283.46
TOTAL	$42,336.99

Respecfully submitted,

[redacted]

Wesley W. Shelton, Jr.
Projector Director

Approved

[redacted]

J.C. Toler, Co-director
Bioengineering Center

cc: Mr. James H. Merritt, USAFSAM/RZP

Georgia Tech

Georgia Institute of Technology
Centennial Research Building
400 Tenth Street, N.W.
Atlanta, Georgia 30332-0130

BIOENGINEERING CENTER
404•894•3964
FAX: 404•894•3120

14 January 1991

Department of the Air Force
Air Force Systems Command
Aeronautical Systems Division/PMRSC
Wright-Patterson AFB, OH 4533-6503

Contract No.: F33615-87-D-0626
Item No.: 0001 Sequence No.:13

James C. Toler, Director
Bioelectromagnetics Laboratory
Co-Director, Bioengineering Center
(404) 894-3964

Norberto F. Ezquerra, Director
Medical Informatics Laboratory
(404) 894-7026

Philip R. Kennedy, Director
Neuroscience Laboratory
(404) 894-4257

Michael J. Sinclair, Director
Robotics and Microelectronics Laboratory
(404) 894-4931

KEY STAFF

David M. Banks
(404) 894-7020

Stephen J. Bonasera
(404) 894-7031

Michael F. Burrow
(404) 894-7034

John W. Peifer
(404) 894-7028

Wesley W. Shelton, Jr.
(404) 894-8727

Thomas G. Single
(404) 894-7033

Crystal L. Tucker
(404) 894-7022

Reference: Contract No. F33615-87-D-0626, Delivery Order 0013, "Development of High Power Microwave Devices for Use in Bioeffects Studies," Georgia Tech Project No. B-10-A13

Subject: Performance and Cost Report No. 8
Reporting Period: 1 November 1990 to 30 November 1990

Gentlemen:

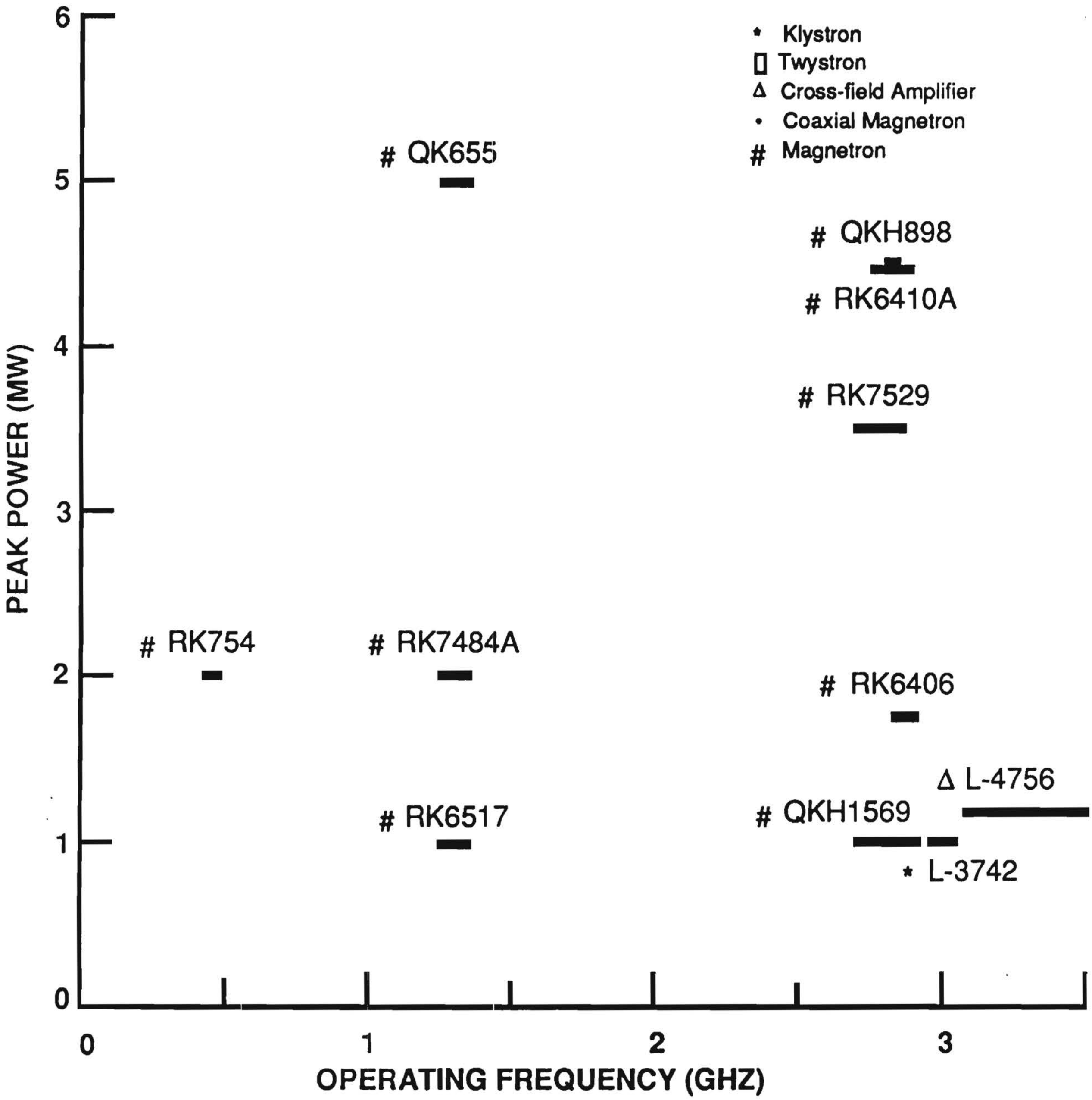
This Delivery Order specifies an engineering study which will culminate in recommendations in equipment designs and configurations that might best simulate field parameters likely to be encountered in high power microwave research and operations. In formulating design recommendations, considerations are to include the use of conventional as well as novel sources, single and multiple antennas (phased arrays), conformal arrays, and other such designs as may be considered practicable in the present state-of-the-art. A written report of recommendations, including suggested designs and configurations at the block diagram and/or conceptual drawing level of detail, will be delivered at the end of the study period.

I. PERFORMANCE REPORT

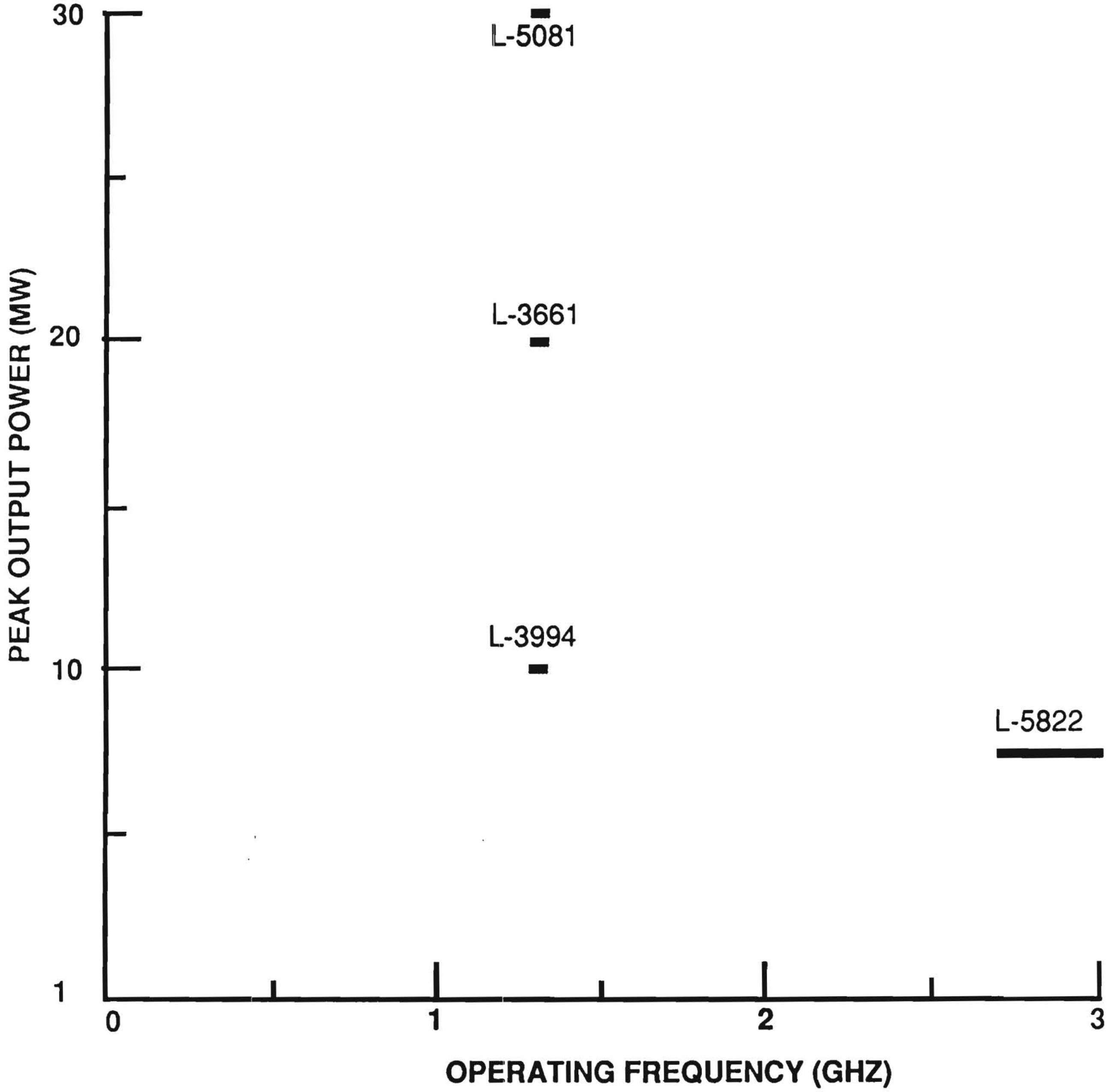
During this reporting period work was focussed primarily on intensive study and analysis of manufacturer-supplied technical literature (Varian, Hughes, Raytheon, EEV, Litton) on readily-available transmitter tubes. Effort was expended in clarifying errors and ambiguities present in several brochures. Two manufacturers (Varian and Raytheon) were also contacted with regard to complete transmitter systems: they agreed to generate design plans and forward them along with cost estimates. Additionally, initial reviews of information pertaining to entire, surplus radar systems (including transmitters and antennas) were begun.

This report features 15 transmitter tubes, selected from the technical literature, which are specified as operating in the UHF (0.406 GHz), L, and S (3.51 GHz) frequency bands (or, using the new designations, the upper C-band through the lower F-band) and producing peak output powers on the order of 1.0 MW to 30 MW. Included in this report are four Litton transmitter tubes with the capability of peak power outputs of 7.5 MW, 10 MW, 20 MW, and 30 MW respectively. The added special problems of operating these higher-power tubes (e.g., extra cooling demands, arcing, etc.) are not addressed in this report. .

Company	Model	Peak Output Power (MW)	Ave. Output Power (kW)	Operating Freq. (GHz)	Duty Cycle	Pulse Width (μsec)	Weight (Lb.)	Length (In.)	Tube Type
Litton									
	L-3661	20	-	1.3	-	-	-	-	Klystron
	L-3742	1	-	2.98-3.1	-	-	-	-	Klystron
	L-3994	10	-	1.3	-	-	-	-	Klystron
	L-5081	30	-	1.3	-	-	-	-	Klystron
	L-5882	7.5	-	2.7-3.0	-	-	-	-	Klystron
	L-4756	1.2	-	3.09-3.51	0.025	110	-	-	Cross-field Amp.
Raytheon									
	RK754	2	-	0.406-0.450	0.0018	7	220	-	Magnetron
	RK7484A	2	-	1.25-1.35	0.0012	3	90	-	Magnetron
	RK6517	1	-	1.25-1.35	0.0013	3	90	-	Magnetron
	RK7529	3.5	_	2.7-2.85	0.0008	2	66	-	Magnetron
	RK6410A	4.5	_	2.75-2.86	0.001	2	57	-	Magnetron
	RK6406	1.75	-	2.85-2.91	0.007	2	40	-	Magnetron
	QK655	5	-	1.25-1.35	0.0018	6	110	-	Magnetron
	QKH898	4.5	-	2.841-2.871	0.001	3	60	-	Magnetron
	QKH1569	1	-	2.7-2.9	0.001	1	66	-	Magnetron



HPM Figure 2. Peak powers of several microwave transmitters plotted against frequency ranges of operation as specified by the



HPM Figure 3. Peak powers of several very high-power Litton **klystron** microwave transmitters plotted against frequency ranges of operation as specified by the manufacturer.

HPM Table 2 tabulates the 15 transmitter tubes along with operating parameters specified by the respective manufacturers. HPM Figure 2 plots the peak output powers of the 11 lower peak-power tubes vs the frequency ranges over which they are specified to operate and HPM Figure 3 plots the higher peak-power tubes.

The information presented for these devices is just for single device operations. The feasibility of amplifier chains to achieve even higher peak powers is possible.

II. COST REPORT

Costs incurred during the November 1990 period were:

Personal Services	$ 0.00
Fringe Benefits	$ 0.00
Materials and Supplies	$ 0.00
Travel	$ 0.00
Computer	$ 0.00
Overhead	$ 0.00
TOTAL	$ 0.00

Cumulative costs incurred through November 1990 were:

Personal Services	$18,030.58
Fringe Benefits	$ 4,742.05
Materials and Supplies	$ 948.06
Travel	$ 2,332.84
Computer	$ 0.00
Overhead	$16,283.46
TOTAL	$42,336.99

Respecfully submitted,

[redacted]

Wesley W. Shelton, Jr.
Projector Director

Approved

[redacted]

J.C. Toler, Co-director
Bioengineering Center

cc: Mr. James H. Merritt, USAFSAM/RZP

Georgia Tech

Georgia Institute of Technology
Centennial Research Building
400 Tenth Street, N.W.
Atlanta, Georgia 30332-0130

BIOENGINEERING CENTER
404•894•3964
FAX: 404•894•3120

8 February 1991

Department of the Air Force
Air Force Systems Command
Aeronautical Systems Division/PMRSC
Wright-Patterson AFB, OH 4533-6503

Contract No.: F33615-87-D-0626
Item No.: 0001 Sequence No.:13

James C. Toler, Director
Bioelectromagnetics Laboratory
Co-Director, Bioengineering Center
(404) 894-3964

Norberto F. Ezquerra, Director
Medical Informatics Laboratory
(404) 894-7026

Philip R. Kennedy, Director
Neuroscience Laboratory
(404) 894-4257

Michael J. Sinclair, Director
Robotics and Microelectronics Laboratory
(404) 894-4931

KEY STAFF

David M. Banks
(404) 894-7020

Stephen J. Bonasera
(404) 894-7031

Michael F. Burrow
(404) 894-7034

John W. Peifer
(404) 894-7028

Wesley W. Shelton, Jr.
(404) 894-8727

Thomas G. Single
(404) 894-7033

Crystal L. Tucker
(404) 894-7022

Reference: Contract No. F33615-87-D-0626, Delivery Order 0013, "Development of High Power Microwave Devices for Use in Bioeffects Studies," Georgia Tech Project No. B-10-A13

Subject: Performance and Cost Report No. 9
Reporting Period: 1 December 1990 to 31 December 1990

Gentlemen:

This Delivery Order specifies an engineering study which will culminate in recommendations in equipment designs and configurations that might best simulate field parameters likely to be encountered in high power microwave research and operations. In formulating design recommendations, considerations are to include the use of conventional as well as novel sources, single and multiple antennas (phased arrays), conformal arrays, and other such designs as may be considered practicable in the present state-of-the-art. A written report of recommendations, including suggested designs and configurations at the block diagram and/or conceptual drawing level of detail, will be delivered at the end of the study period.

I. PERFORMANCE REPORT

During this reporting period work was directed at commercially available high-power, continuous-wave microwave amplifier tubes and transmitters, in contrast with the high peak-power emphasis of recent months. Contacts with manufacturers' representatives were made to achieve a better understanding of the availability and true capabilities of their power devices.

HPM Table 3 tabulates, and HPM Figure 4 plots, the characteristics of 9 Varian klystron tubes for which the output power capabilities are specified to be 100 kW or greater. The information presented for these devices is just for single device operations, and the feasibility of amplifier chains to achieve even higher CW powers is being investigated.

II. COST REPORT

Incremental funding for this project has not been provided, and the Cost Report, therefore, reflects no changes from the preceding Performance & Cost Report.

Costs incurred during the December 1990 period were:

Personal Services	$ 0.00
Fringe Benefits	$ 0.00
Materials and Supplies	$ 0.00
Travel	$ 0.00
Computer	$ 0.00
Overhead	$ 0.00
TOTAL	$ 0.00

Cumulative costs incurred through December 1990 were:

Personal Services	$18,030.58
Fringe Benefits	$ 4,742.05
Materials and Supplies	$ 948.06
Travel	$ 2,332.84
Computer	$ 0.00
Overhead	$16,283.46
TOTAL	$42,336.99

Respectfully submitted,

[redacted]

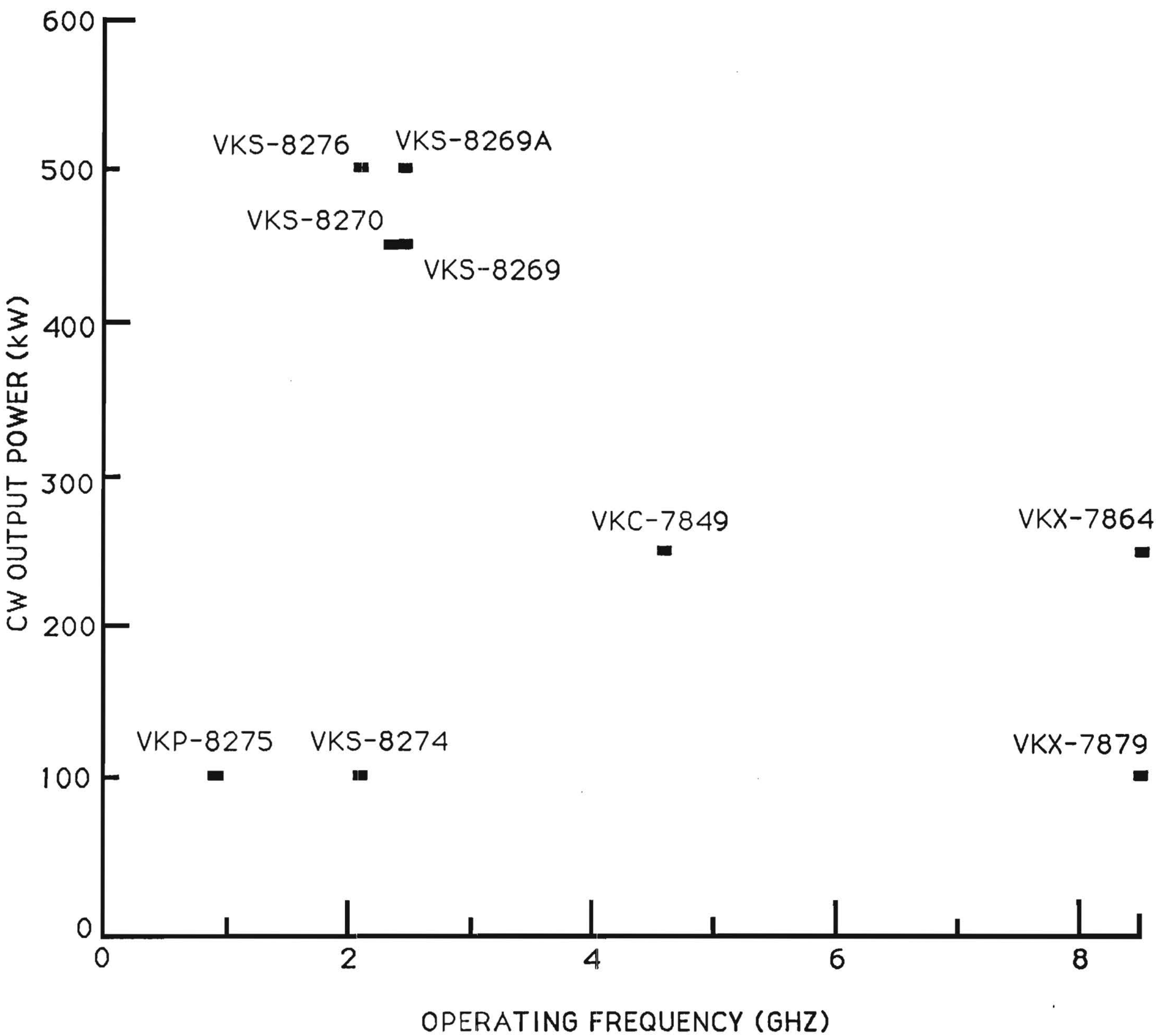
Wesley W. Shelton, Jr.
Projector Director

Approved
[redacted]
J.C. Toler, Co-director
Bioengineering Center

cc: Mr. James H. Merritt, USAFSAM/RZP

HPM Table 3

Company	Model	Peak Output Power (MW)	CW Output Power (kW)	Operating Freq. (GHz)	Duty Cycle	Pulse Width (μsec)	Weight (Lb.)	Length (In.)	Tube Type
Varian									
	VKP-8275	-	100	0.910-0.920	-	-	325	70	CW Klystron
	VKS-8274	-	100	2.106-2.122	-	-	250	54	CW Klystron
	VKS-8276	-	500	2.114	-	-	700	79	CW Klystron
	VKS-8270	-	450	2.370-2.390	-	-	680	75	CW Klystron
	VKS-8269	-	450	2.440-2.460	-	-	680	75	CW Klystron
	VKS-8269A	-	500	2.440-2.460	-	-	680	75	CW Klystron
	VKC-7849	-	250	4.6	-	-	640	49	CW Klystron
	VKX-7864	-	250	8.5	-	-	450	48	CW Klystron
	VKX-7879	-	100	8.5	-	-	360	44	CW Klystron



HPM Figure 4. Continuous-wave (CW) output power capabilities of nine Varian high-power CW klystron microwave tubes plotted against frequency ranges of operation as specified by the manufacturer.

Georgia Tech

Georgia Institute of Technology
Centennial Research Building
400 Tenth Street, N.W.
Atlanta, Georgia 30332-0130

BIOENGINEERING CENTER
404•894•3964
FAX: 404•894•3120

25 March 1991

Department of the Air Force
Air Force Systems Command
Aeronautical Systems Division/PMRSC
Wright-Patterson AFB, OH 4533-6503

Contract No.: F33615-87-D-0626
Item No.: 0001 Sequence No.:13

James C. Toler, Director
Bioelectromagnetics Laboratory
Co-Director, Bioengineering Center
(404) 894-3964

Norberto F. Ezquerra, Director
Medical Informatics Laboratory
(404) 894-7026

Philip R. Kennedy, Director
Neuroscience Laboratory
(404) 894-4257

Michael J. Sinclair, Director
Robotics and Microelectronics Laboratory
(404) 894-4931

KEY STAFF

David M. Banks
(404) 894-7020

Stephen J. Bonasera
(404) 894-7031

Michael F. Burrow
(404) 894-7034

John W. Peifer
(404) 894-7028

Wesley W. Shelton, Jr.
(404) 894-8727

Thomas G. Single
(404) 894-7033

Crystal L. Tucker
(404) 894-7022

Reference: Contract No. F33615-87-D-0626, Delivery Order 0013, "Development of High Power MIcrowave Devices for Use in Bioeffects Studies," Georgia Tech Project No. B-10-A13

Subject: Performance and Cost Report No. 10
Reporting Period: 1 January 1991 to 31 January 1991

Gentlemen:

This Delivery Order specifies an engineering study which will culminate in recommendations in equipment designs and configurations that might best simulate field parameters likely to be encountered in high power microwave research and operations. In formulating design recommendations, considerations are to include the use of conventional as well as novel sources, single and multiple antennas (phased arrays), conformal arrays, and other such designs as may be considered practicable in the present state-of-the-art. A written report of recommendations, including suggested designs and configurations at the block diagram and/or conceptual drawing level of detail, will be delivered at the end of the study period.

I. PERFORMANCE REPORT

During this reporting period work focussed on preliminary designs incorporating the various transmitter capabilities previously investigated into systems for simulating high-power microwave environments likely to be encountered by Air Force technical personnel. Considerations included modelling far-field power density levels with both pulsed and continuous-wave operation. The modelling included the effects of beamshaping and gain due to various antenna geometries and the contribution of multipath The search for additional high-power transmitting instrumentation was continued, but at a lower level of effort. A review of continuous-wave microwave transmitters was also begun.

II. COST REPORT

Incremental funding for this project has not been provided, and the Cost Report, therefore, reflects no charges made directly against this project's account. Upon receipt of the incremental funding, the charges incurred will be transferred to this project's account and specified in that month's Cost report.

Respectfully submitted,

[redacted]

Wesley W. Shelton, Jr.
Projector Director

Approved

[redacted]

J.C. Toler, Co-director
Bioengineering Center

cc: Mr. James H. Merritt, USAFSAM/RZP

Georgia Tech

Georgia Institute of Technology
Centennial Research Building
400 Tenth Street, N.W.
Atlanta, Georgia 30332-0130

BIOENGINEERING CENTER
404•894•3964
FAX: 404•894•3120

25 March 1991

Department of the Air Force
Air Force Systems Command
Aeronautical Systems Division/PMRSC
Wright-Patterson AFB, OH 4533-6503

Contract No.: F33615-87-D-0626
Item No.: 0001 Sequence No.:14

James C. Toler, Director
Bioelectromagnetics Laboratory
Co-Director, Bioengineering Center
(404) 894-3964

Norberto F. Ezquerra, Director
Medical Informatics Laboratory
(404) 894-7026

Philip R. Kennedy, Director
Neuroscience Laboratory
(404) 894-4257

Michael J. Sinclair, Director
Robotics and Microelectronics Laboratory
(404) 894-4931

KEY STAFF

David M. Banks
(404) 894-7020

Stephen J. Bonasera
(404) 894-7031

Michael F. Burrow
(404) 894-7034

John W. Peifer
(404) 894-7028

Wesley W. Shelton, Jr.
(404) 894-8727

Thomas G. Single
(404) 894-7033

Crystal L. Tucker
(404) 894-7022

Reference: Contract No. F33615-87-D-0626, Delivery Order 0013, "Development of High Power Microwave Devices for Use in Bioeffects Studies," Georgia Tech Project No. B-10-A13

Subject: Performance & Cost-Cumulative Reporting Period: 1 November 1990 to 31 January 1991

Gentlemen:

This Delivery Order specifies an engineering study which will culminate in recommendations in equipment designs and configurations that might best simulate field parameters likely to be encountered in high power microwave research and operations. In formulating design recommendations, considerations are to include the use of conventional as well as novel sources, single and multiple antennas (phased arrays), conformal arrays, and other such designs as may be considered practicable in the present state-of-the-art. A written report of recommendations, including suggested designs and configurations at the block diagram and/or conceptual drawing level of detail, will be delivered at the end of the study period.

I. CUMULATIVE PERFORMANCE REPORT

During this reporting quarter efforts were directed primarily toward acquiring and evaluating technical literature pertaining to commercially available, off-the-shelf, high-power microwave transmitter tubes. These devices were reviewed especially with regard to megawatt peak-power transmission capabilities. Other factors considered included frequency ranges of operation, pulse widths, duty cycles, and physical aspects such as size, weight, cooling requirements, etc. The findings gleaned from manufacturers' technical literature and phone conversations with technical representatives were summarized by HPM Figures 2 and 3, and HPM Table 2 in the Performance and Cost Report for November 1990, and by HPM Figure 4 and HPM Tables 3 in the Performance and Cost Report for December 1990. A review of continuous-wave transmitter capabilities was also begun. Conceptualizations of possible system configurations suitable for simulating the environments specified for this task were initiated. Appropriate antenna types, waveguide "plumbing," and the physical environments likely to be encountered were included in formulating the system configurations.

II. CUMULATIVE COST REPORT

Incremental funding for this project was not available until mid-February, 1991. The cumulative cost summary, therefore, remains as reported in January's Performance & Cost Report.

Cumulative costs incurred through February 1991 were:

Personal Services	$18,030.58
Fringe Benefits	$ 4,742.05
Materials and Supplies	$ 948.06
Travel	$ 2,332.84
Computer	$ 0.00
Overhead	$16,283.46
TOTAL	$42,336.99

Respectfully submitted,

[redacted]

Wesley W. Shelton, Jr.
Projector Director

Approved

[redacted]

J.C. Toler, Co-director
Bioengineering Center

cc: Mr. James H. Merritt, USAFSAM/RZP

Georgia Tech

Georgia Institute of Technology
Centennial Research Building
400 Tenth Street, N.W.
Atlanta, Georgia 30332-0130

BIOENGINEERING CENTER
404•894•3964
FAX: 404•894•3120

25 March 1991

Department of the Air Force
Air Force Systems Command
Aeronautical Systems Division/PMRSC
Wright-Patterson AFB, OH 4533-6503

Contract No.: F33615-87-D-0626
Item No.: 0001 Sequence No.: 13

James C. Toler, Director
Bioelectromagnetics Laboratory
Co-Director, Bioengineering Center
(404) 894-3964

Norberto F. Ezquerra, Director
Medical Informatics Laboratory
(404) 894-7026

Philip R. Kennedy, Director
Neuroscience Laboratory
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Michael J. Sinclair, Director
Robotics and Microelectronics Laboratory
(404) 894-4931

KEY STAFF

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Stephen J. Bonasera
(404) 894-7031

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(404) 894-7034

John W. Peifer
(404) 894-7028

Wesley W. Shelton, Jr.
(404) 894-8727

Thomas G. Single
(404) 894-7033

Crystal L. Tucker
(404) 894-7022

Reference: Contract No. F33615-87-D-0626, Delivery Order 0013, "Development of High Power Microwave Devices for Use in Bioeffects Studies," Georgia Tech Project No. B-10-A13

Subject: Performance and Cost Report No. 11
Reporting Period: 1 February 1991 to 31 February 1991

Gentlemen:

This Delivery Order specifies an engineering study which will culminate in recommendations in equipment designs and configurations that might best simulate field parameters likely to be encountered in high power microwave research and operations. In formulating design recommendations, considerations are to include the use of conventional as well as novel sources, single and multiple antennas (phased arrays), conformal arrays, and other such designs as may be considered practicable in the present state-of-the-art. A written report of recommendations, including suggested designs and configurations at the block diagram and/or conceptual drawing level of detail, will be delivered at the end of the study period.

I. PERFORMANCE REPORT

During this reporting period work continued on the design of transmitting systems to simulate high-power microwave environments likely to be encountered by Air Force technical personnel. Additionally, analysis of propagation of such power levels over short distances representative of working environments was begun.

II. COST REPORT

Incremental funding for this project arrived in mid-February and was in the process of being activated at the time of issuance the monthly cost-accounting reports pertinent to this Performance and Cost Report. Therefore, the Cost Report for this reporting month will be deferred until the Performance and Cost report for March 1991 is submitted.

Costs incurred during the February 1991 period were:

Personal Services	$	19,024:38
Fringe Benefits	$	5,003.41
Materials and Supplies	$	0.00
Travel	$	989.80
Computer	$	0.00
Overhead	$	16,892.63
TOTAL	$	40,653.58

Cumulative costs incurred through February 1991 were:

Personal Services	$	46,854.96
Fringe Benefits	$	12,322.86
Materials and Supplies	$	948.06
Travel	$	3,322.64
Computer	$	0.00
Overhead	$	39,655.33
TOTAL	$	103,103.85

Respectfully submitted,

[redacted]

Wesley W. Shelton, Jr.
Projector Director

Approved

[redacted]

J.C. Toler, Co-director
Bioengineering Center

cc: Mr. James H. Merritt, USAFSAM/RZP

Georgia Tech

Georgia Institute of Technology
Centennial Research Building
400 Tenth Street, N.W.
Atlanta, Georgia 30332-0130

BIOENGINEERING CENTER
404•894•3964
FAX: 404•894•3120

25 March 1991

Department of the Air Force
Air Force Systems Command
Aeronautical Systems Division/PMRSC
Wright-Patterson AFB, OH 4533-6503

Contract No.: F33615-87-D-0626
Item No.: 0001 Sequence No.:14

James C. Toler, Director
Bioelectromagnetics Laboratory
Co-Director, Bioengineering Center
(404) 894-3964

Norberto F. Ezquerra, Director
Medical Informatics Laboratory
(404) 894-7026

Philip R. Kennedy, Director
Neuroscience Laboratory
(404) 894-4257

Michael J. Sinclair, Director
Robotics and Microelectronics Laboratory
(404) 894-4931

KEY STAFF

David M. Banks
(404) 894-7020

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(404) 894-7031

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(404) 894-7034

John W. Peifer
(404) 894-7028

Wesley W. Shelton, Jr.
(404) 894-8727

Thomas G. Single
(404) 894-7033

Crystal L. Tucker
(404) 894-7022

Reference: Contract No. F33615-87-D-0626, Delivery Order 0013, "Development of High Power Microwave Devices for Use in Bioeffects Studies," Georgia Tech Project No. B-10-A13

Subject: R&D Status Report-Cumulative
Reporting Period: 1 November 1990 to 31 January 1991

Gentlemen:

This Delivery Order specifies an engineering study which will culminate in recommendations in equipment designs and configurations that might best simulate field parameters likely to be encountered in high power microwave research and operations. In formulating design recommendations, considerations are to include the use of conventional as well as novel sources, single and multiple antennas (phased arrays), conformal arrays, and other such designs as may be considered practicable in the present state-of-the-art. A written report of recommendations, including suggested designs and configurations at the block diagram and/or conceptual drawing level of detail, will be delivered at the end of the study period.

R&D STATUS REPORT

During this reporting quarter efforts were directed primarily toward acquiring and evaluating technical literature pertaining to commercially available, off-the-shelf, high-power microwave transmitter tubes. These devices were reviewed especially with regard to megawatt peak-power transmission capabilities. Other factors considered included frequency ranges of operation, pulse widths, duty cycles, and physical aspects such as size, weight, cooling requirements, etc. The findings gleaned from manufacturers' technical literature and phone conversations with technical representatives were summarized by HPM Figures 2 and 3, and HPM Table 2 in the Performance and Cost Report for November 1990, and by HPM Figure 4 and HPM Table 3 in the Performance and Cost Report for December 1990. A review of continuous-wave transmitter capabilities was also begun. Conceptualizations of possible system configurations suitable for simulating the environments specified for this task were initiated. Appropriate antenna types, waveguide "plumbing," and the physical environments likely to be encountered were included in formulating the system configurations.

Respectfully submitted,

[redacted]

Wesley W. Shelton, Jr.
Projector Director

Approved

[redacted]

J.C. Toler, Co-director
Bioengineering Center

cc: Mr. James H. Merritt, USAFSAM/RZP

Georgia Tech

Georgia Institute of Technology
Centennial Research Building
400 Tenth Street, N.W.
Atlanta, Georgia 30332-0130

BIOENGINEERING CENTER
404•894•3964
FAX: 404•894•3120

2 October 1990

Department of the Air Force
Air Force Systems Command
Aeronautical Systems Division/PMRSC
Wright-Patterson AFB, OH 4533-6503

Contract No.: F33615-87-D-0626-0013
Item No.: 0001 Sequence No.: 1

James C. Toler, Director
Bioelectromagnetics Laboratory
Co-Director, Bioengineering Center
(404) 894-3964

Norberto F. Ezquerra, Director
Medical Informatics Laboratory
(404) 894-7026

Philip R. Kennedy, Director
Neuroscience Laboratory
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(404) 894-8727

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(404) 894-7033

Crystal L. Tucker
(404) 894-7022

Reference: Contract No. F33615-87-D-0626, Delivery Order 0013,"Development of High Power Microwave Devices for Use in Bioeffects Studies," Georgia Tech Project No. B-03-A13

Subject: R & D Status Report - Cumulative
Reporting Period: 2 May 1990 to 31 July 1990

Gentlemen:

This Delivery Order specifies an engineering study which will culminate in recommendations in equipment designs and configurations that might best simulate field parameters likely to be encountered in high power microwave research and operations. In formulating design recommendations, considerations are to include the use of conventional as well as novel sources, single and multiple antennas (phased arrays), conformal arrays, and other such designs as may be considered practicable in the present state-of-the-art. A written report of recommendations, including suggested designs and configurations at the block diagram and/or conceptual drawing level of detail, will be delivered at the end of the study period.

CUMULATIVE STATUS REPORT

During this cumulative reporting period, efforts were concentrated on the acquisition of the technical literature pertaining to power sources and antenna systems that might be used in the simulation designs specified for this study. Analysis of performance capabilities (e.g., output power, pulse-width, PRF) for candidate devices and cost comparisons was begun. The development of software to assist in the simulation design was also begun.

Respectfully submitted,

[redacted]

W.W. Shelton, Jr.
Project Director

Approved

[redacted]

J.C Toler, Co-Director
Bioengineering Center

cc: Mr. Jim Merritt, USAFSAM/RZP

DEVELOPMENT OF HIGH POWER MICROWAVE DEVICES FOR USE IN BIOEFFECTS STUDIES

FINAL REPORT DRAFT

Project No. B-03-A13

January 1992

Research Contract No. F33615-87-D-0626/0013

By

Wesley W. Shelton

Prepared for

U.S. Air Force School of Aerospace Medicine
Radiation Sciences Division
Brooks AFB, TX 78235

By

Bioengineering Research Center
Office of Interdisciplinary Programs
Georgia Institute of TEchnology
Atlanta, GA 30332

PREFACE

This Final Report describes the results of research and development pertinent to U.S. Air Force Contract No. FF33615-87-D-0626/0013 "Development of High Power Microwave Devices for Use in Bioeffects Studies," for the Radiation Sciences Division of the U.S. Air Force School of Aerospace Medicine, Brooks AFB, TX. The work was performed by personnel in the Bioengineering Research Center at the Georgia Institute of Technology, Atlanta, GA. The work is identified at Gerogia Tech as Project No. B-03-A13. Dr. Wesley W. Shelton served as the Project Director.

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INTRODUCTION

Advances in microwave and millimeter-wave radar transmitter tube development have pushed the peak output powers up to tens of megawatts of peak power and up to the megawatt range for continuous wave (CW) systems. These extremely high power transmitter devices coupled with high gain antennas can produce effective radiated powers (ERP) on the order of many gigawatts (GW). For instance, a 20 megawatt (MW), peak power, transmitter tube coupled with a 40 dB antenna can produce an ERP of 200 GW. A 1 MW CW transmitter coupled with the same antenna will produce an ERP of 10 GW. The energy produced by these high power systems can be continuous wave or pulsed with different pulse widths and pulse repetition frequencies (prf). The energy ranges in frequency from the ultra high frequency band (UHF, 300 MHz-1 GHz), through the L-band (1 GHz-2 GHz), S-band (2 GHz-4 GHz), C-band (4 GHz-8 GHz), and the K-band (8 GHz-40 GHz), as well as the millimeter-wave region above 40 GHz.

The widespread use of high power radar systems in research and development environments and in operational circumstances makes it imperative to investigate the possibilities of any bioeffects and/or health effects that might occur from acute or chronic exposure to those systems by Air Force personnel in the course of their contact with them.

Two basic environments were envisioned in this project. The first was an external environment where the high power exposure occured by virtue of energy propagation over the terrain. Free space scenarios were assumed to compute representative power densities and specific absorption rates for high power radar simulations. The second environment pertained to high power microwave (HPM) research, development, and testing within workspaces. In this case, waveguide and resonant cavity concepts were applied at lower frequencies of interest and, as the frequencies increased, free space propagation concepts were applied. Representative computations of power densities and SAR values were made under conditions of simplifying assumptions. The methods and techniques used in these analyses can be adapted to the geometries and conditions of specific radar sites and workspaces of interest, but here they will serve to provide general estimates of what might be encountered and suggest experimental simulations.

TERRESTRIAL PROPAGATION

In estimating field strengths or power densities to be achieved along a path of electromagnetic energy propagation, two major groups of considerations were addressed.

The first group were those over which the path designer could exercise a great degree of control, and were related to the transmitter site and operation:

- o transmitter output power
- o antenna (or antenna array) gain
- o polarization at the antenna
- o pulse or continuous wave transmission

The second group of considerations affecting propagation related to the physical and chemical aspects of the atmosphere and the earth's surface along the propagation path. They served to alter the direction of energy propagation, attenuate the energy along the propagation path, and cause refractions and reflections which could give rise to multipath phenomena. These factors do not lend themselves to control or manipulation by the path designer, especially for long paths. Included were:

- o earth's surface
    - smoothness vs roughness
    - permittivity
    - conductivity
    - curvature
    - flatness
    - diffractive obstacles
    - vegetative absorption
    - orientation with respect to polarization

o atmosphere
    absorption
    refraction
    reflection
    ducting

Figure 1 depicts a path profile geometry with line-of-sight propagation features expected of transmission at approximately VHF or higher frequencies.

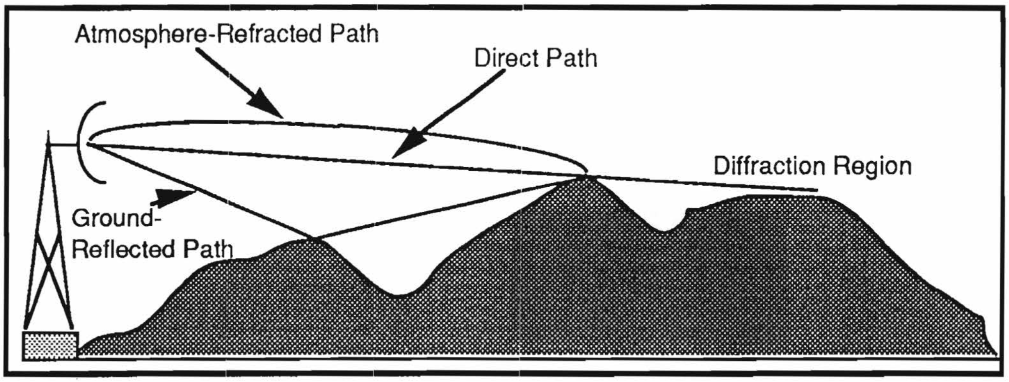

Figure 1. Basic geometry for a line-of-sight propagation analysis showing direct, ground-reflected, and atmosphere-refracted ray paths and a diffraction region behind a diffracting obstacle along the path.

Transmitter Site

The transmitter site could be fixed or mobile: here, it was anticipated that a fixed site would be used. The principal factors of interest then were the output power capability of the transmitter (pulsed or CW operation), the maximum achievable gain of the antenna or antenna array, the polarization of the transmitted energy, and the choice of pulsed or CW operation.

The transmitter system is built around the source of power generation. For one-way transmission, the design is simplified and less expensive, since receiver devices are not needed as in the case of radar. The design goal, here, is to select and assemble the tube, amplifiers, modulator (if needed), cooling equipment, waveguide, etc., in such a way as to produce the maximum output power achievable without causing damage to any of the components. Two possible approaches to providing a transmitter (UHF or higher) are to procure a complete (or almost complete) radar system from Air Force or DOD inventories or design from the ground up and construct a tailored system using off-the-shelf components.

A number of complete radar systems appeared to meet the needs of this project from the standpoint of high power performance capabilities. Availability of the radar systems described here was not investigated in great depth, but they were known to exist in the DOD's inventory or advertised in some sales literature as surplus government equipment. Availability at the time of purchase must be ascertained, since the availability can be expected to change over periods of months or years. The systems discussed here are generally complete with cooling systems, antenna systems, and other equipment pertaining to radar functions.

AN/FPS 6	Height Finder Radar (1,2)	
	elevation beamwidth	0.90
	azimuth beamwidth	3.20
	pulsewidth	$2\mu s$
	PRF	300/400 Hz
	peak power	4.5 MW
	frequency	2.7-2.9 GHz
	manufacturer	-
	note: antenna is 30' x 7' reflector	

AN/FPS 8	Search Radar (2)	
	elevation beamwidth	-
	azimuth beamwidth	-
	pulsewidth	$3\mu s$
	PRF	360 Hz
	peak power	1MW
	frequency	1.28-1.35 GHz
	manufacturer	General Electric

note: antenna is 25' parabolic

AN/FPS 16	Monopulse Tracking Radar (3)	
	elevation beamwidth	1.10
	azimuth beamwidth	1.10
	pulsewidth	0.25-1.0 μs
	PRF	160-1707 Hz
	peak power	1 MW (5.48 GHz)
	frequency	5.4-5.9 GHz
	manufacturer	-
	note: antenna is 3.7 m reflector	
AN/FPS 71	Search Radar (2)	
	elevation beamwidth	-
	azimuth beamwidth	-
	pulsewidth	2μs
	PRF	400 Hz
	peak power	5 MW
	frequency	1.25-1.35 GHz
	manufacturer	Raytheon
	note: antenna is 40' reflector	
AN/TPS 37	Height Finder Radar (2)	
AN/MPS 16	elevation beamwidth	-
	azimuth beamwidth	-
	pulsewidth	2.5μs
	duty cycle	0.0009
	peak power	1MW
	frequency	5.2-5.3 GHz
	manufacturer	Avco
	note: antenna is 21' x 5.5' parabolic, AN/MPS 16 operates with 60 Hz, AN/TPS 37 operates with 400 Hz input	
AN/TPS 43E	3D Search- Height Finder Stacked Beam Radar (1,2)	
	elevation beamwidth (approx.)	1.1
	azimuth beamwidth	-
	pulsewidth	6.5μs
	PRF (6 staggered) (average)	250 Hz
	peak power	4MW
	frequency	2.9-3.1 GHz

	manufacturer	Westinghouse
ARSR-3	Air Route Surveillance Radar (4)	
	elevation beamwidth	-
	azimuth beamwidth	1.250
	pulsewidth	2μs
	PRF	310-365 Hz
	peak power	5 MW
	frequency	1.25-1.35 GHz
	manufacturer	Westinghouse
	note: average power is 3.6 KW	
ASR-8	Airport Surveillance Radar (4)	
	elevation beamwidth	-
	azimuth beamwidth	1.350
	pulsewidth	0.6μs
	PRF	700-1200 Hz
	peak power	1.4 MW
	frequency	2.7-2.9 GHz
	manufacturer	Westinghouse
	note: average power is 875 W	

An alternative to the acquisition of entire already-existing radar systems (or portions of them) is the design and construction of the transmitter from the "ground up" with off-the-shelf transmitter tubes and supporting devices (amplifiers, etc.) An advantage to this approach is that the designer is not constrained to the operating parameters inherent to the acquired system and can design for frequency, PRF, CW or pulse operation, and other parameters which meet specific needs that might vary from site-to-site. The lower cost of this approach could be another advantage, but it would require significantly greater design effort than involved in merely putting already-existing systems into operation. An additional advantage might include the option allowed the designer to incorporate "higher-technology" components into the transmitter to create "smart" transmitter systems or systems capable of operating with a wider selection of performance parameters.

The designs of interest here were for high-power, one-way transmissions and, therefore, eliminated the need for receiver-function devices such as TR switches, circulators, down-converters, receiver amplifiers, and filters which would accompany fully-complete radar systems. For instance, Figure 2 is a basic block diagram of a moving target indicator (MTI) radar system with a power-amplifier transmitter (4). The system components which would be retained for transmitter purposes are those shown within the shaded area. The duplexer, for instance, would be eliminated since its function is the isolation of the transmitted and received

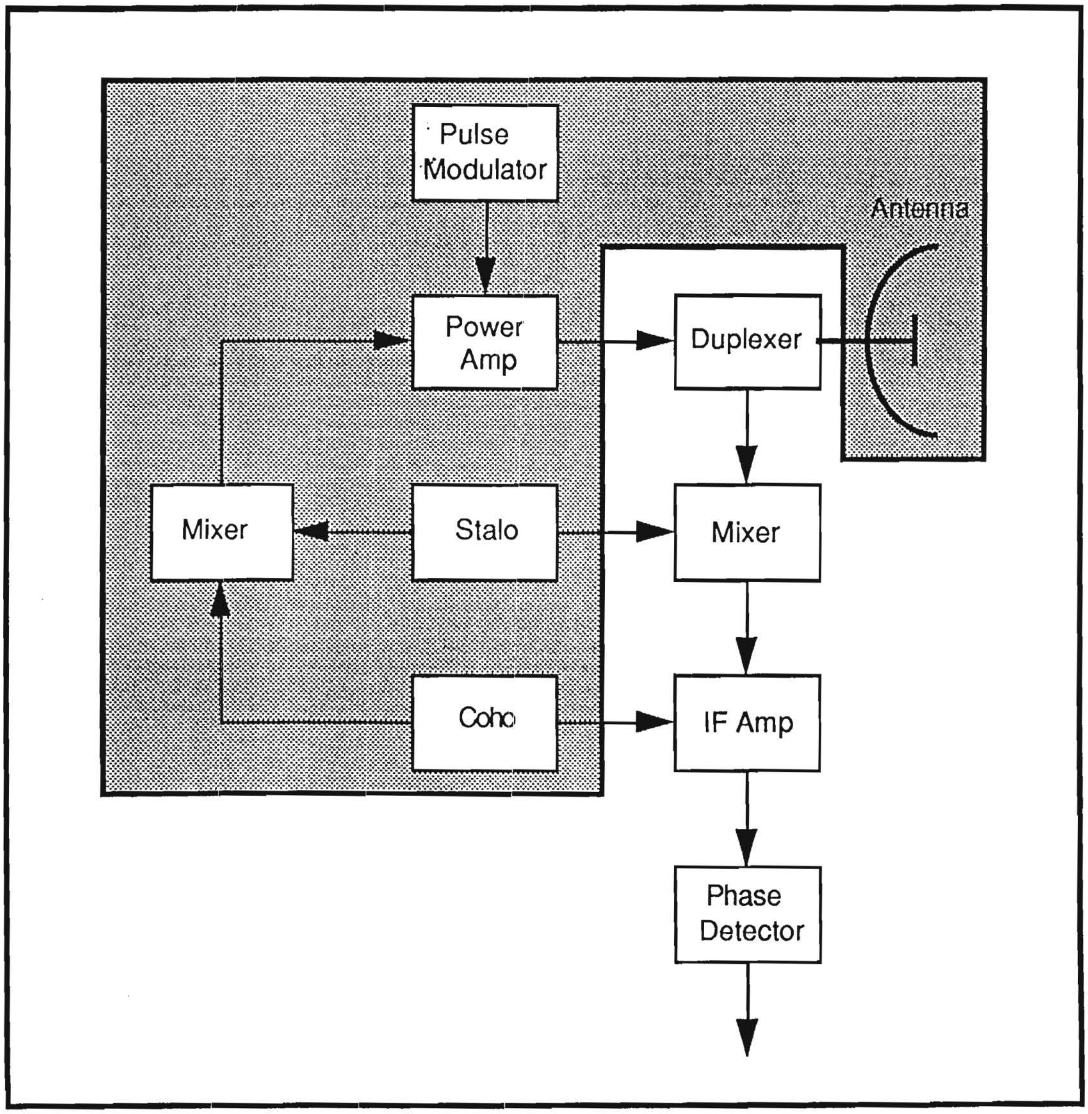

Figure 2. Basic block diagram of an MTI (moving target indicator) radar system. The components serving the transmit function of the system are enclosed within the shaded portion (Stalo=stable oscillator, Coho=coherent oscillator).

signals. Prominent radar tube manufacturers were contacted to obtain technical literature for devices which operate at frequencies from UHF through C-band, especially at high output powers. Hughes, EEV, Raytheon, Varian, Litton, Ma/Com, and Thomson-CSF were the manufacturers (with proven track records of high-quality, reliable devices) who responded with applicable literature and other technical information. Raytheon, Thomson-CSF and Varian were also very cooperative in providing technical information regarding the devices listed in their brochures as well as some which were not yet readily available. The initial search for tubes focussed on those devices capable of peak-power outputs of 1 MW or greater. Tables 1 and 2 and Figures 3, 4, and 5 summarize the essential characteristics of those devices identified as potentially applicable to the needs of this project. Tables 3,4, and 5 provide capability data for just Thomson-CSF devices. Thomson-CSF also produces a gyrotron, model TH 1504, capable of 1 MW peak output power at 8 GHz with a maximum pulse width of 1 s The device is 305 cm in length and weighs 2100 kg.

CW high power levels are substantially less than the peak power levels characteristic of the pulsed systems. Figure 6 depicts graphically the output power capabilities of nine Varian high-power klystron CW tubes. Tables 6 and 7 list CW tubes possessing the highest powers among all those reviewed in the technical literature received. Therefore, achieving large power densities at distances greater than a few thousand feet is even more difficult than in the pulsed transmission case.

The radar tube information detailed in this report provides a starting point for the designer. In order to enhance power outputs, the designer will need to determine exactly how much power is needed, given distances, antenna gains, antenna arrays, etc., and then resort to measures such as amplifier chain systems and combiner networks to achieve those power levels.

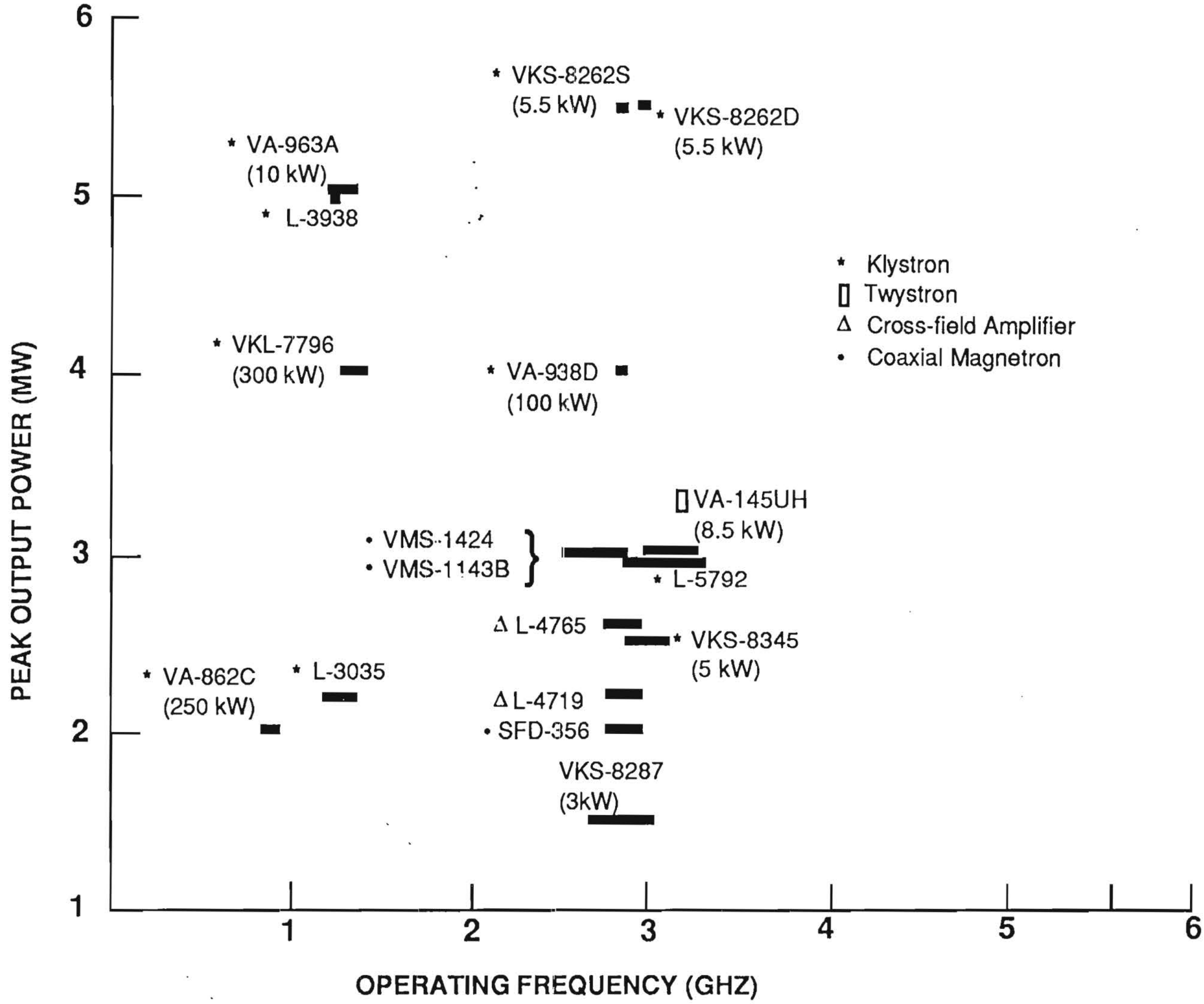

Figure 3. Peak output powers of microwave transmitters plotted against frequency ranges of operation as specified by the respective manufacturers. Average output powers are given in parentheses when specified by the manufacturers.

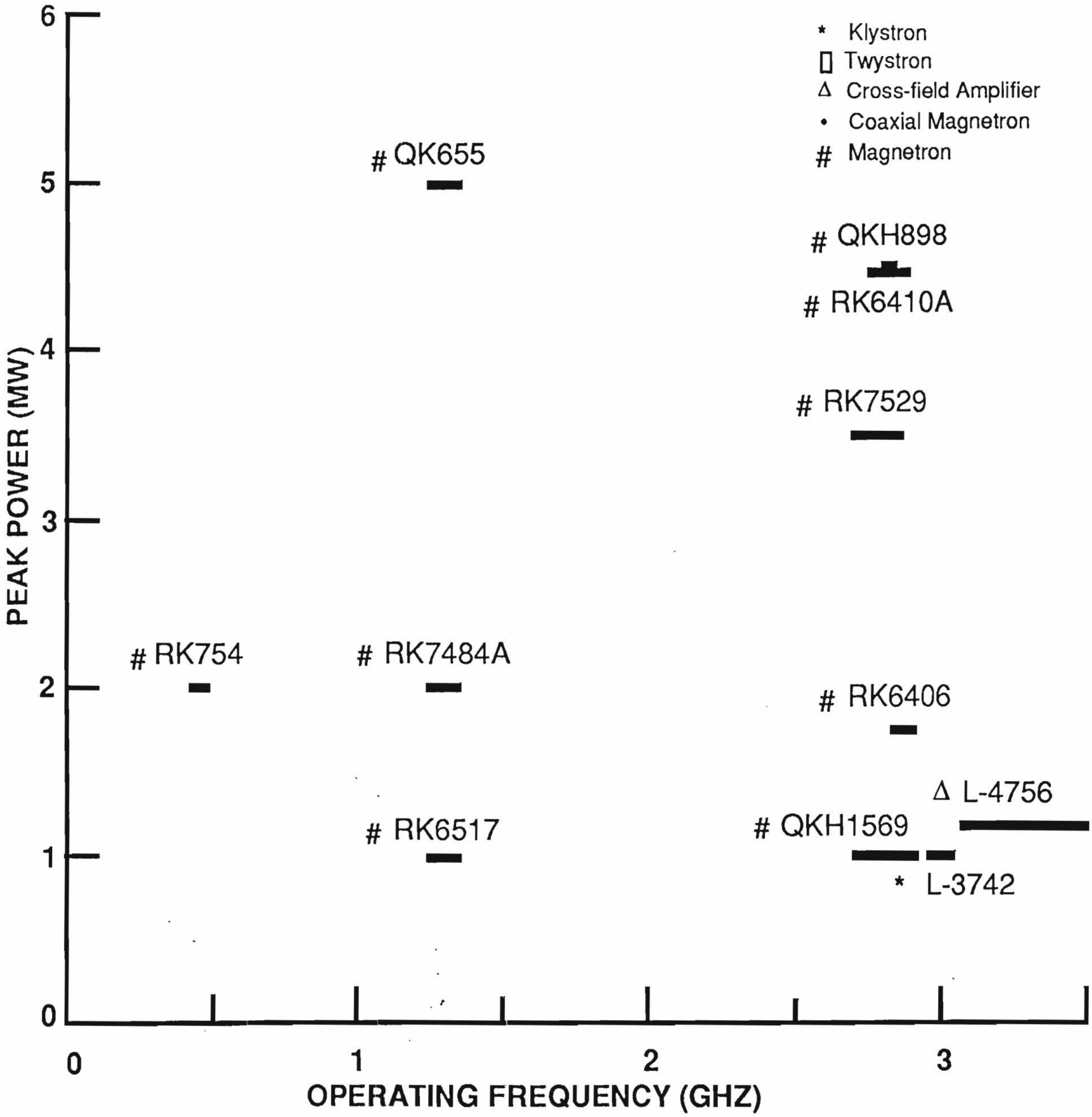

Figure 4. Additional peak output powers of microwave transmitters plotted against frequency ranges of operation as specified by the respective manufacturers. Average output powers are given in parentheses when specified by the manufacturers.

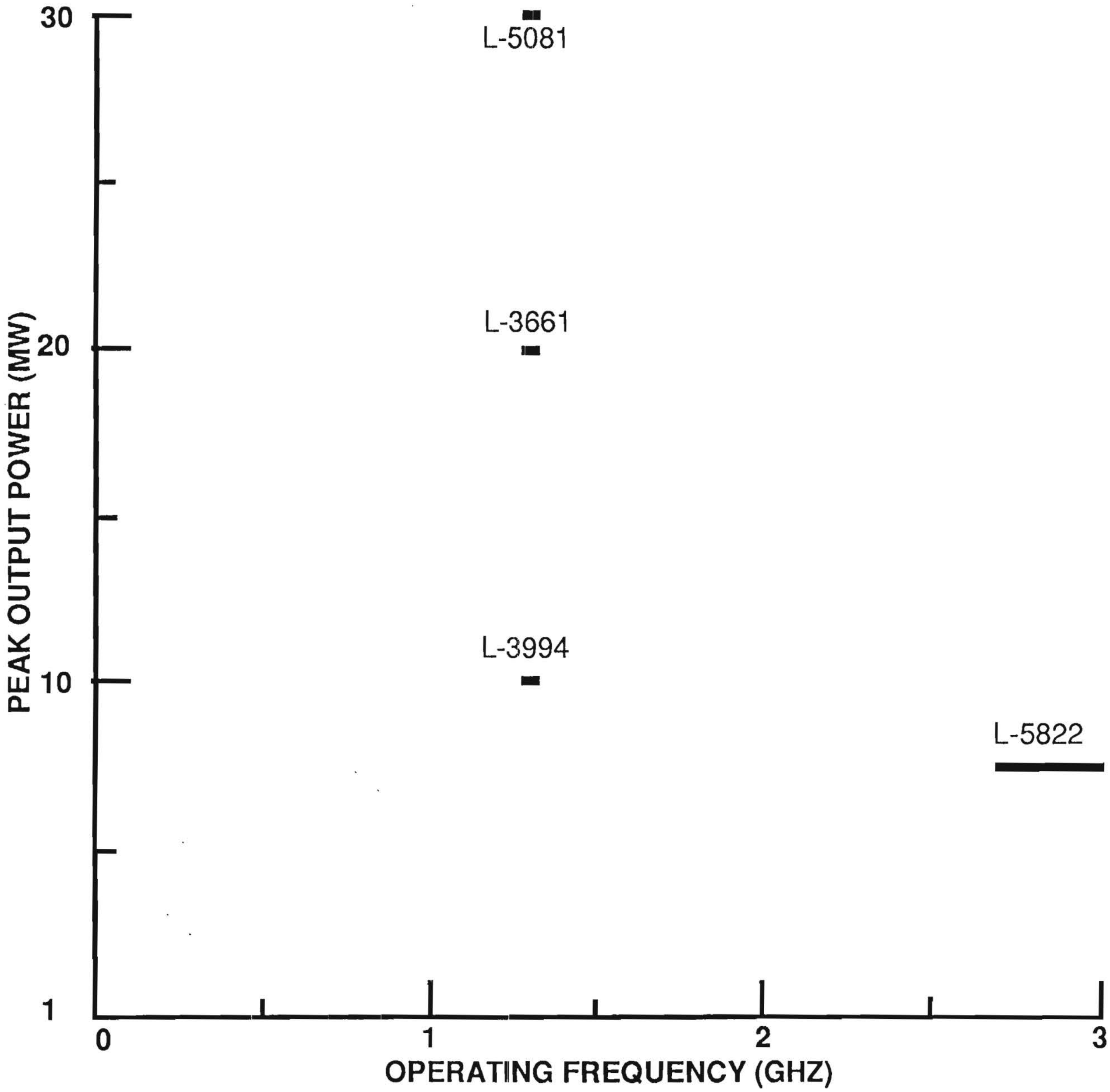

Figure 5. Peak powers of several very high power Litton klystron microwave transmitter tubes plotted against frequency ranges of operation as specified by the manufacturer.

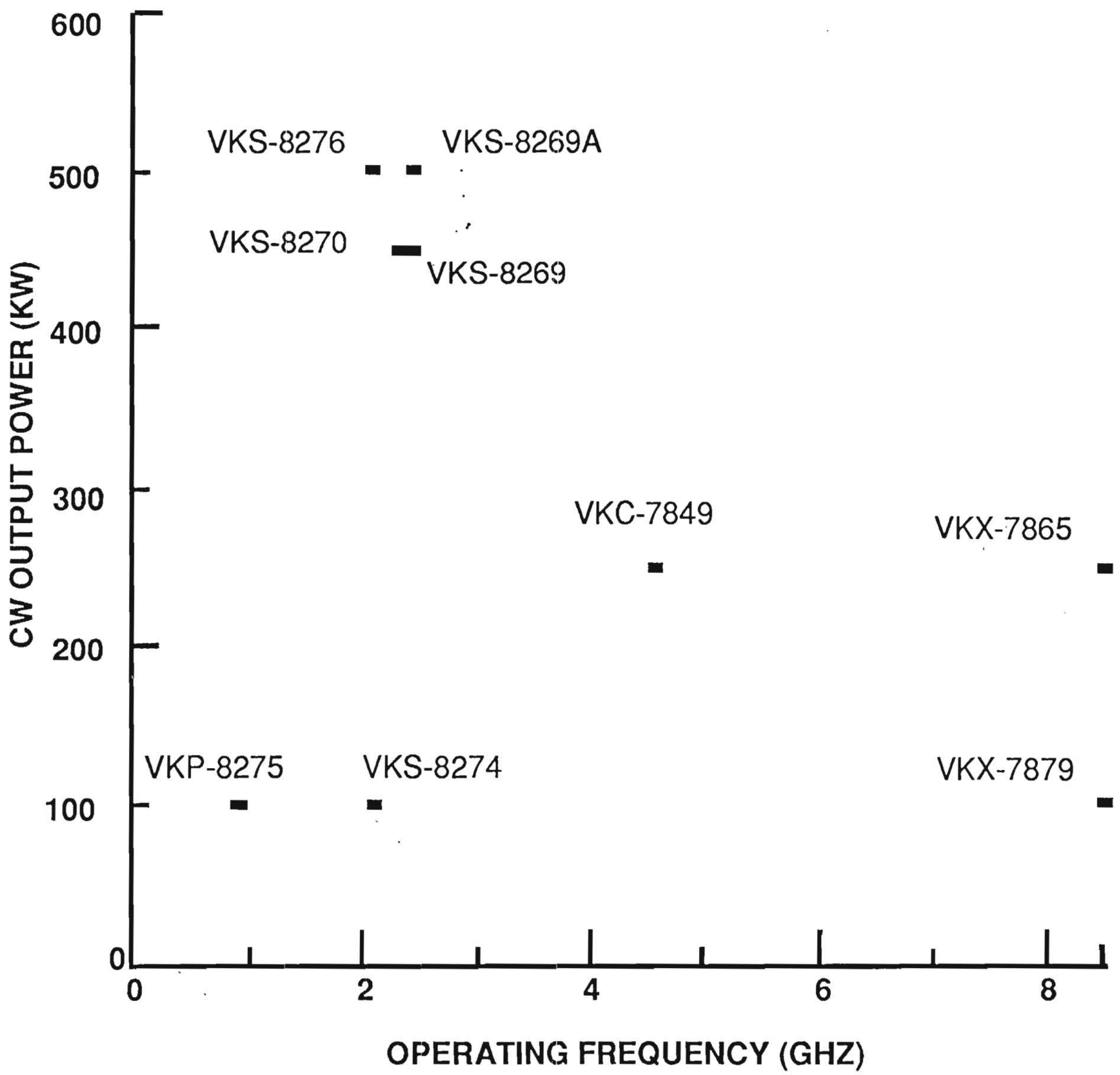

Figure 6. Continuous-wave (CW) output power capabilities of nine Varian high-power klystron microwave tubes plotted against frequency ranges of operation as specified by the manufacturer.

Company	Model	Peak Output Power (MW)	Ave. Output Power (kW)	Operating Freq. (GHz)	Duty Cycle	Pulse Width (μsec)	Weight (Lb.)	Length (In.)	Tube Type
Varian									
	VMS-1424	3	-	2.7-2.9	-	-	-	-	Coax Magnetron
	VMS-1143B	3	-	2.7-2.9	-	-	-	-	Coax Magnetron
	SFD-356	2	-	2.85-2.91	-	-	-	-	Coax Magnetron
	SFD-356D	2	-	2.85-2.91	-	-	-	-	Coax Magnetron
	VA-862C	2	250	0.928-0.938	0.125	10000	800	110	Klystron
	VKL-7796	4	300	1.29-1.36	0.075	130	600	95	Klystron
	VA-963A	5	10	1.25-1.35	0.002	3	150	60	Klystron
	VKS-8287	1.5	3	2.7-3.0	0.002	6	90	38	Klystron
	VA-938D	4	100	2.856	0.025	20	580	64	Klystron
	VKS-8345	2.5	5	2.9-3.1	0.002	7	140	43	Klystron
	VKS-8262S	5.5	5.5	2.865	0.001	5	100	35	Klystron
	VKS-8262	5.5	5.5	2.999	0.001	5	150	40	Klystron
	VA-145UH	3	8.5	3.015-3.215	0.0025	10	140	42	Twystron
Litton									
	L-3035	2.2	-	1.24-1.36	0.003	-	-	-	Klystron
	L-3938	5	-	1.3	0.03	-	-	-	Klystron
	L-4719	2.2	-	2.9-3.1	0.0125	28	-	-	Cross-field Amp.
	L-4765	2.6	-	2.9-3.1	0.0053	28	-	-	Cross-field Amp.
	L-5792	3	-	2.9-3.3	0.002	-	-	-	Klystron

Table 1. A summary of operating parameters of several Litton and Raytheon transmitter tubes.

Company	Model	Peak Output Power (MW)	Ave. Output Power (kW)	Operating Freq. (GHz)	Duty Cycle	Pulse Width (μsec)	Weight (Lb.)	Length (In.)	Tube Type
Litton									
	L-3661	20	-	1.3	-	-	-	-	Klystron
	L-3742	1	-	2.98-3.1	-	-	-	-	Klystron
	L-3994	10	-	1.3	-	-	-	-	Klystron
	L-5081	30	-	1.3	-	-	-	-	Klystron
	L-5882	7.5	-	2.7-3.0	-	-	-	-	Klystron
	L-4756	1.2	-	3.09-3.51	0.025	110	-	-	Cross-field Amp.
Raytheon									
	RK754	2	-	0.406-0.450	0.0018	7	220	-	Magnetron
	RK7484A	2	-	1.25-1.35	0.0012	3	90	-	Magnetron
	RK6517	1	-	1.25-1.35	0.0013	3	90	-	Magnetron
	RK7529	3.5	-	2.7-2.85	0.0008	2	66	-	Magnetron
	RK6410A	4.5	-	2.75-2.86	0.001	2	57	-	Magnetron
	RK6406	1.75	-	2.85-2.91	0.007	2	40	-	Magnetron
	QK655	5	-	1.25-1.35	0.0018	6	110	-	Magnetron
	QKH898	4.5	-	2.841-2.871	0.001	3	60	-	Magnetron
	QKH1569	1	-	2.7-2.9	0.001	1	66	-	Magnetron

Table 2. A summary of several Raytheon transmitter tubes and Litton very-high power transmitter tubes.

Model	Peak Output Power (MW) (Typical)	Ave. Output Power (kW) (Typical)	Operating Freq. (GHz)	Duty Cycle	Pulse Width (μsec) (max.)	Weight (kg)	Length (cm)
TV 2022	20	40	1.3	-	8	760	200
TV 2022A	20	50	1.3	-	8	760	200
TV 2022B	20	60	1.3	-	10	760	200
TV 2022D	30	60	1.3	-	7	760	200
TV 2019W	10	18	2.856	-	10	405	130
TH 2128	35	17	2.856	-	4.5	620	166
TH 2129	20	30	2.856	-	7.5	510	130
TV 2002	25	8	2.856 or 2.998	-	6	420	140
TV 2012	5	10	2.856 or 2.998	-	10	405	130
TV 2015	25	25	2.856 or 2.998	-	4	410	130
TV 2019	10	15	2.856 or 2.998	-	10	405	130
F 2040	25	15	2.998	-	6	550	164
F 2042	30	30	2.998	-	6	600	166
F 2043	20	5	2.998	-	3	480	170
TH 2056	5	12	2.998	-	6	405	130
TH 2066	5.5	5.5	2.998	-	7.5	455	134
TH 2066U	7.5	7.5	2.998	-	5	455	134
TH 2074	6	6	2.998	-	7.5	260	95
TH 2094	35	17.5	2.998	-	4.5	620	166
TH 2100	35	17.5	2.998	-	4.5	620	166
TH 2100A	35	17.5	2.998	-	4.5	620	166
TH 2100B	40	20	2.998	-	4.5	620	166
TH 2109	25	25	2.998	-	5	470	160
TH 2132	45	20	-	-	4.5	630	166
TH2067	5	1	5.71		5	250	97

Table 3. A summary of Thomson-CSF high power, short and medium pulse klystrons for scientific applications in the L- , S- , and C- bands. The weight of the focussing electromagnet is included in the weight.

Model	Peak Output Power (MW)	Ave. Output Power (kW)	Operating Freq. (GHz)	Duty Cycle	Pulse Width (μsec) (max.)	Weight (kg)	Length (cm)	Tube Type
TH 2068	3.5	6	1.25-1.35	-	8	100	167	Klystron
TH 2068A	3	6	1.25-1.35	-	8	100	167	Klystron
TH 2068B	4	8.5	1.25-1.35	-	8	100	167	Klystron
TH 2096	4	12	1.25-1.37	-	11	120	167	Klystron
TV 2092	7.5	185	classified	-	500	120	180	Klystron
TV 2030	20	20	classified	-	4	65	130	Klystron
TH 2091	20	20	classified	-	4	80	170	Klystron
TH 2098	3.4	8.5	2.715-2.915	-	10	65	125	Klystron
TH 2116	3	8	2.715-2.930	-	10	65	125	Klystron
TH 2117	3.4	10	2.9-3.1	-	8	65	125	Klystron
MCV 1352	2.125	-	1.27-1.32	0.0012	5	-	-	Magnetron
MC 567	2.4	-	1.22-1.37	0.00125	5	-	-	Magnetron
TH 3095	2	-	1.305-1.365	0.0012	5	-	-	Magnetron
MCV 1353	2.125	-	1.315-1.370	0.0012	5	-	-	Magnetron

Table 4. A summary of operating parameters of Thomson-CSF high power pulsed klystrons and magnetrons. The exact operating frequencies of the TV 2092, TV 2030, and TH 2091 are listed by the manufacturer as classified, but are listed as being in the S-band .

Model	Peak Output Power (MW) (Typical)	Ave. Output Power (kW) (Typical)	Operating Freq. (GHz)	Duty Cycle	Pulse Width (μsec) (max.)	Weight (kg)	Length (cm)
TH 2140	4	5	0.428	-	50	1200	320
TH 2134	2	100	0.432	-	1000	1200	400
TH 2118	6	200	0.433	-	220	1800	375
TH 2131	12	21	0.805	-	115	800	350
TH 2138	1.25	75	0.85		2000	350	220
TH 2104 A	5	150	1.296	-	600	900	205
TH 2115	2	150	1.3	-	1000	860	220
TH 2095A	6.25	45	1.3	-	310	820	200
TH 2104	15	50	1.3	-	100	840	210
TH 2104	10	100	1.3	-	200	840	210
TH 2104U	10	250	1.3	-	250	900	205
TV 2022C	20	10	1.3	-	20	760	200
TH 2097	4	25	2.856	-	100	410	130
TH 2097	12	25	2.856	-	30	410	130
TH 2097	20	25	2.856	-	20	410	130
TV 2013	4	60	2.9985	-	15	431	136
TH 2108	5	60	2.9985	-	15	431	136
TH 2090	15	30	2.9985	-	12	425	135
TH 2130	20	20	2.9985	-	20	460	150
TH 2130V	20	20	2.9985	-	20	460	150

Table 5. Summary of Thomson-CSF high power, long pulse klystrons for scientific applications in the UHF- , L- , and C- bands. The weight of the focussing electromagnet is included in all the weights except for the TH 2138 which has no focussing electromagnet. The TH 2140, TH 2134, and TH 2118 models have integral focussing electromagnets.

Company	Model	Peak Output Power (MW)	CW Output Power (kW)	Operating Freq. (GHz)	Duty Cycle	Pulse Width (μsec)	Weight (Lb.)	Length (In.)	Tube Type
Varian									
	VKP-8275	-	100	0.910-0.920	-	-	325	70	CW Klystron
	VKS-8274	-	100	2.106-2.122	-	-	250	54	CW Klystron
	VKS-8276	-	500	2.114	-	-	700	79	CW Klystron
	VKS-8270	-	450	2.370-2.390	-	-	680	75	CW Klystron
	VKS-8269	-	450	2.440-2.460	-	-	680	75	CW Klystron
	VKS-8269A	-	500	2.440-2.460	-	-	680	75	CW Klystron
	VKC-7849	-	250	4.6	-	-	640	49	CW Klystron
	VKX-7864	-	250	8.5	-	-	450	48	CW Klystron
	VKX-7879	-	100	8.5	-	-	360	44	CW Klystron

Table 6. A summary of Varian high power CW transmitter tubes

Model	Peak Output Power (MW)	CW Output Power (MW)	Operating Freq. (GHz)	Duty Cycle	Pulse Width (μsec)	Weight (kg)	Length (cm)
TH 2089	NA	1	0.352	NA	NA	1800	475
TH 2105	NA	1	0.508	NA	NA	1350	215
TH 2103	NA	0.5	3.7	NA	NA	400	202

Table 7. A summary of Thomson-CSF high power CW klystrons for scientific applications.

Antenna Concepts

The transmitter output power is coupled to an antenna by means of cable or waveguide in order to achieve efficient transmission into free space. The antenna will focus the larger portion of the input energy into a main beam (and a number of minor, or smaller, beams) at whose geometric center (ideally) the power will be substantially greater than that which would be achieved in the absence of the antenna. The general measure of this improvement in power brought about by an antenna is called the "gain" of the antenna. Generally, the larger the aperture dimensions of the antenna with respect to the wavelength of the transmitted energy, the narrower the main beam and the more it approaches a "pencil beam" shape. Or, alternatively, as the frequency of operation increases with respect to a fixed-size aperture, the narrower the main beam becomes. The fundamental expression in antenna theory (5) which relates the gain of an antenna transmitting at a wavelength λ to its maximum effective aperture area A is

$$G = \frac{4\pi A}{\lambda^2}. \tag{1}$$

It must be kept in mind that this gain value refers to the peak value obtained at the geometric (ideally) center of the main beam of the antenna's radiation pattern.

The product of the transmitter output power and the gain calculated (or measured) above is the effective radiated power or ERP. For instance: a transmitter output of 3 MW coupled, without waveguide losses, to an antenna with a 40 dB (a factor of 10,000) gain will produce an ERP of 30 GW.

The antenna aperture dimensions also determine the free-space distance from the antenna at which the transmitted electromagnetic wavefront becomes a "uniform plane wave." This distance is conditioned upon the amount of phase difference across the plane wavefront that is tolerable to the designer, and this distance is generally referred to as the beginning of the "far field." Electromagnetic energy emitted from an antenna aperture is generally qualified as being in the "far-field" region, with respect to that aperture, at a range in excess of

$$R_f = 2\frac{D^2}{\lambda}, \tag{2}$$

where λ = wavelength of the transmitted energy and
D = greatest dimension of the aperture.

Equation (2) corresponds to the condition that at distance R_f the propagating energy will have achieved plane wave status with phase variation no greater than $\lambda/16$ across the wavefront and the magnitude of the field exhibiting an inverse dependence on the range, $1/R$, where $R>R_f$. Another far-field range criterion,

$$R_f = \frac{D^2}{\lambda}, \tag{3}$$

is employed when a greater phase variation (on the order $\lambda/8$) over the wavefront is acceptable. At lower frequencies where the maximum aperture dimension may be small compared to a wavelength, ranges greater than $2D^2/\lambda$ may be required to achieve acceptable constraints on the planewave phase variations (5).

Power Density in the Far-Field

In free-space (i.e., no reflecting or diffracting bodies present along the path), an antenna with a gain, G_t, ideally produces a far-field power density given, at a range of R meters as

$$S = \frac{P_t G_t}{4\pi R^2} \ \text{W/m}^2, \tag{4}$$

where P_t = transmitted power in watts,
G_t = antenna gain and
R = range in meters.

It can be noted in Equation (4) that, even in free-space, the power density, S, suffers an attenuation which is inversely proportional to the square of the range. This significant attenuation occurs in the absence of any physical perturbation, but is geometrically founded on the assumption of a spherical wavefront expanding as a function of range (6). For example, consider a sequence of four transmitter output power levels from 1MW to the very high value of 15 MW coupled to antennas with a very high gain of 45 dB. Table 8 lists the theoretical power densities in W/cm^2 at distances from 500 ft to 6,000 ft (one nautical mile) in increments of 500 ft. At one nautical mile, as Table 8 shows, the greatest power density is only on the order of 1 W/cm^2. Figure 7 is a plot of the power density vs range for the example of a 10 MW transmitter and a 45 dB gain antenna.

Transmitter Power (MW)	1	5	10	15
Antenna Gain (dB)	45	45	45	45
Distance (ft)	Power Density (W/cm^2)			
500	10.835	54.174	108.348	162.522
1000	2.709	13.543	27.087	40.630
1500	1.204	6.019	12.039	18.058
2000	0.677	3.386	6.771	10.158
2500	0.433	2.167	4.334	6.501
3000	0.301	1.505	3.010	4.514
3500	0.221	1.106	2.211	3.317
4000	0.169	0.846	1.693	2.539
4500	0.134	0.669	1.338	2.006
5000	0.108	0.542	1.083	1.625
5500	0.090	0.448	0.895	1.343
6000	0.075	0.376	0.752	1.129

Table 8. Computation of power density as a function of distance from antenna aperture (range) for four different transmitter output powers.

This example assumes ideal operating conditions which exclude absorption, scattering, and influence of reflected energy.

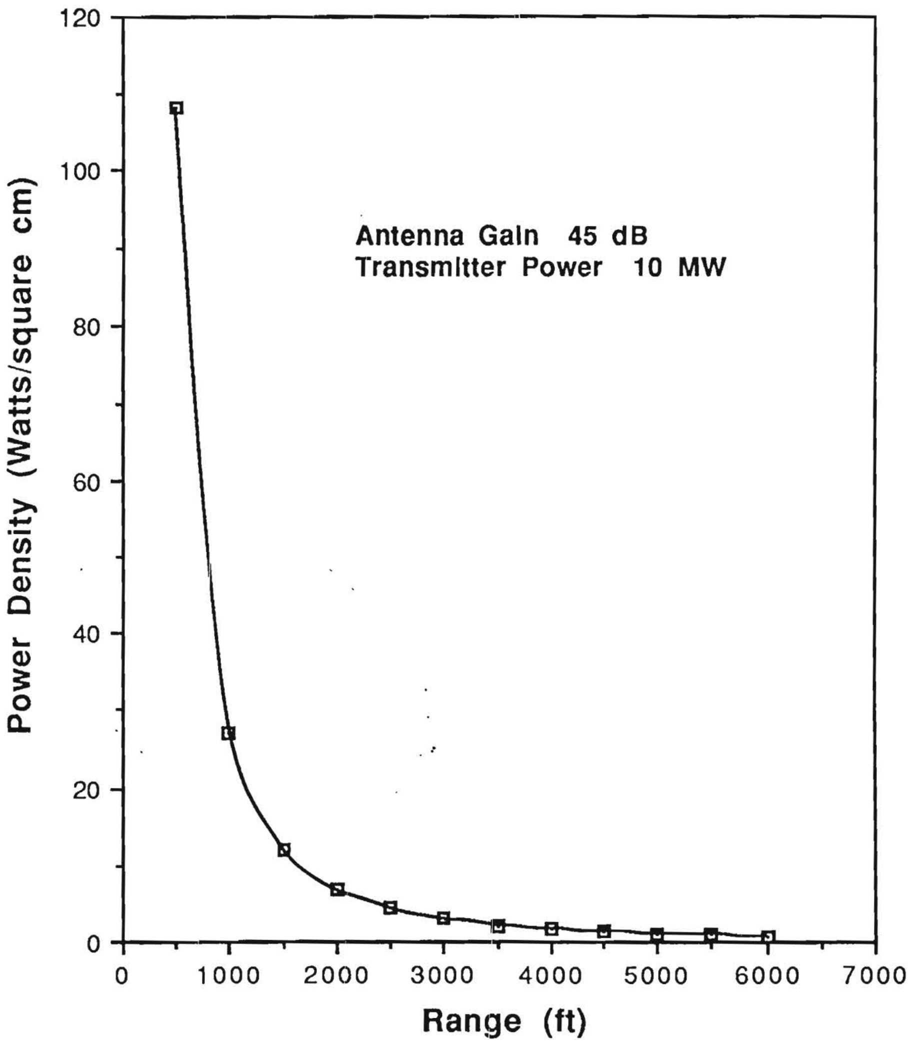

Figure 7. Plot of power density as a function of range for a 10 MW transmitter coupled to a 45 dB gain antenna transmitting into free space.

Antennas exhibit characteristic near-field and far-field radiation patterns which are generally derived from a free-space perspective. When operated in proximity to the earth (and/or other structures), the patterns will be altered by constructive and destructive interference of direct and reflected energy (7). The actual radiating patterns are, therefore, influenced by such factors as the permittivity, conductivity, and roughness of the earth's surface, antenna height, polarization, etc.

Other Factors Affecting Propagation

Multipath

Multipath arises from the reflections which can occur at the earth's surface and refraction in the atmosphere. Generally, the multipath effect is developed in terms of ray theory and often the single-ray approximation in combination with the direct ray is sufficient to characterize reflection and/or refractive propagation dynamics. For a reflecting surface which is "smooth", the reflective properties of the surface depend on the factors mentioned above plus the grazing angle (the angle between the incident energy ray and the horizontal plane through the reflection point) and the polarization of the incident energy with respect to the surface normal.

"Surface roughness" is often based on the "Rayleigh criterion" which considers a surface to be smooth when, referring to Figure 8,

$$h < \frac{1}{8\sin\gamma} \tag{5}$$

where h = the height of any reflection surface irregularity and
γ = grazing angle.

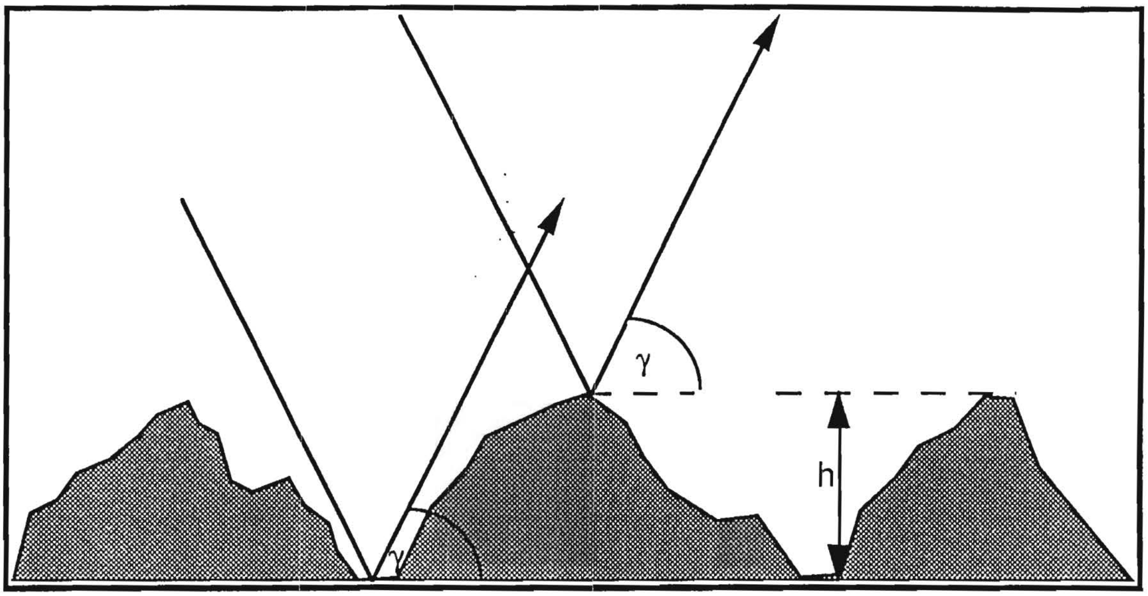

Figure 8. Representation of a reflection point on the earth's surface to illustrate the variables used in the Rayleigh criterion for surface roughness.

A "rough" surface will tend to scatter incident energy in many directions with respect to the local surface normal, thereby producing diffuse reflection. In contrast, a "smooth" surface will reflect significant energy in a preferential direction, and this is referred to as specular reflection. For the propagation geometry pertinent to this project, specularly reflected energy can contribute to the total energy received at a point of interest along the propagation path.

For a surface sufficiently smooth to support specular reflection of electromagnetic energy at frequencies of interest (approximately upper VHF through C-band), theoretical expressions for computing the magnitude and phase of the reflected energy are available. These expressions are functions of the frequency and polarization of the incident energy and the permittivity and conductivity of the reflecting region of the earth's surface.

For the case of horizontal polarization, the reflection coefficient magnitude and phase are calculated using the expression

$$R_h = \frac{\sin\gamma - \sqrt{n^2 - \cos^2\gamma}}{\sin\gamma + \sqrt{n^2 - \cos^2\gamma}} \tag{6}$$

where $n = \sqrt{\varepsilon}$,
$\varepsilon = \varepsilon' - j\varepsilon''$,
$\varepsilon = \varepsilon_r - j\frac{\sigma}{\omega\varepsilon_o}$,
ε_r is the relative permittivity of the local earth,
σ is the conductivity of the local earth in S/m,
ω is the radian frequency and
ε_o is the free space permittivity 8.85×10^{-12} F/m.

For the case of vertical polarization, the applicable expression is

$$R_v = \frac{n^2\sin\gamma - \sqrt{n^2 - \cos^2\gamma}}{n^2\sin\gamma + \sqrt{n^2 - \cos^2\gamma}}. \tag{7}$$

Under the conditions for which the Rayleigh criterion is met, Equations (6) and (7) can be used directly for estimating surface-reflective phenomena. The expressions do not take into account path losses, diffractive effects of path obstacles, or earth curvature. At low grazing angles, both polarizations exhibit nearly 100% reflection of the incident rays while imparting a 180° phase shift. Therefore, for instance, at 0° incidence, the surface reflected wave and the direct wave would ideally be expected to produce total cancellation in the far-field. For an antenna height of 10 ft and a reflection point at 2,000 ft along range, the grazing angle would be approximately 0.3°. The vertical polarization reflection coefficient magnitude would be approximately 0.96 and the phase shift approximately 180°. A 6 ft worker standing upright approximately 1146 ft from the reflection point would encounter a direct-path power density of approximately 0.043 W/cm^2, using Equation (4) with P_t=5 MW and G_t= 30 dB. The worker would also be exposed to a reflected-path (plane-earth geometry) power density approximated by Equation (4). The total length of the reflected path would be the sum of the slant range from the antenna to the reflection point and the slant range from the reflection point to the top of the worker's head. The reflected power term to be used in Equation (4) would be approximately equal to the product of the power emanating from the antenna and the square of the reflection coefficient magnitude at the reflection point. The worker would then be exposed to a total power density of approximately 0.083 W/cm^2. Were the antenna elevated to 50 ft, the incidence angle would become approximately 1.4^o and the reflection coefficient magnitude would decrease to approximately 0.82 while the phase shift would remain roughly the same. In this case, the worker at approximately 245 ft from the reflection point would experience a total power density of approximately 0.142 W/cm^2. For horizontal polarization, the corresponding approximate magnitude and phase values for both cases would be 1.0 and 180^o, respectively. Figures 9, 10, 11, and 12 graphically depict the predicted reflection coefficient behavior as a function of grazing angle for both polarizations over average (e = 15 - j5), smooth earth.

For a multipath model employing a single reflection ray, the difference between the path lengths of the direct and reflected rays can be expressed in terms of an electrical path length difference. For instance, the physical pathlength difference between a direct ray pathlength of 3,000 m and a reflected ray pathlength of 3004.116 m (which represents a case in which reflection occurs 1500 m from the transmitter at an angle of 3^o) is 4.116 m, which translates into an electrical pathlength difference of 137.23 wavelengths at 10 GHz or a net phase shift of $0.23 \times 2\pi = 1.44$ radians (or 82.51^o).

Curvature of Earth's Surface

For the ranges of interest to this project, the earth's curvature does not significantly influence propagation.

Flatness

The terrain over which the propagation takes place may have elevations or crevasses which, depending on the location of the particular site to be simulated, could reduce the strength of the incident field by blocking much of it out. Within reasonable bounds, the path could be physically graded to an acceptable degree of flatness. The natural elevations, contours, etc., along the propagation path can diffract energy into the "shadow" region behind the obstacle and below the geometric line of sight. Depending upon the curvature of the obstacle with respect to the wavelength of the propagating

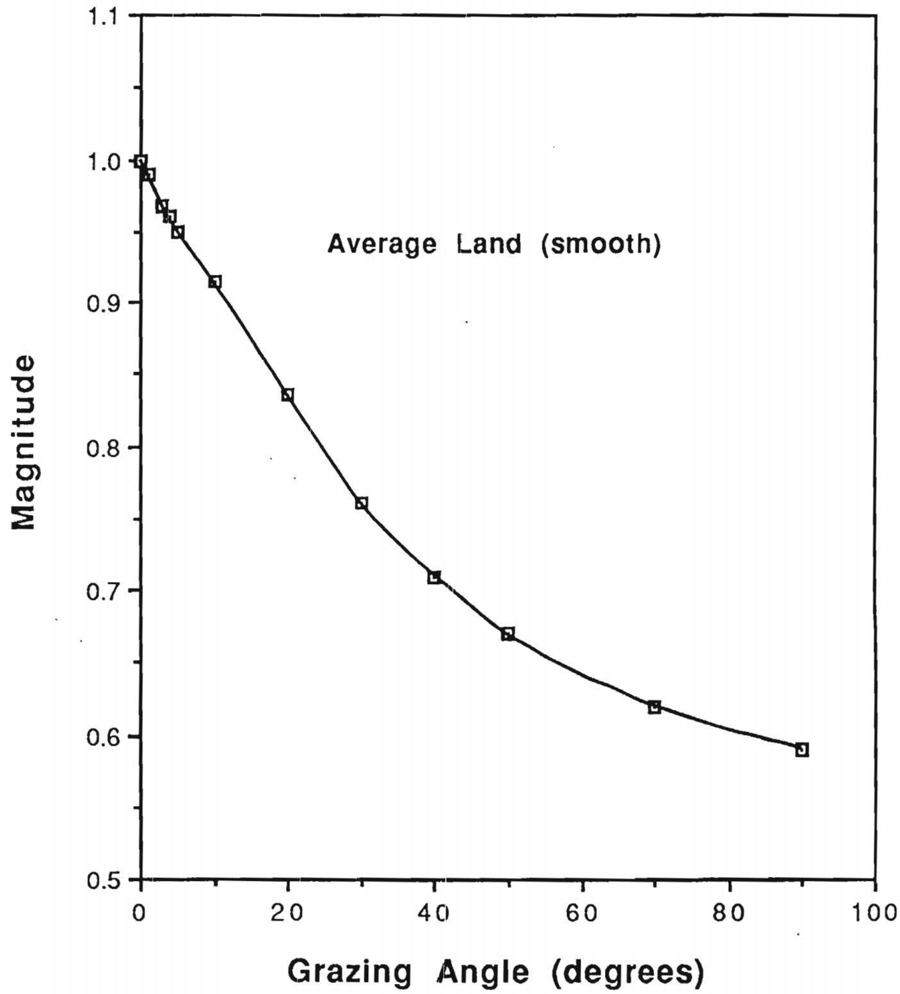

Figure 9. A graph of the magnitude of the horizontal polarization reflection coefficient magnitude versus grazing angle for propagation over average smooth earth at 5 GHz.

energy, caustics may be created and would have to be considered in the path analysis (8).

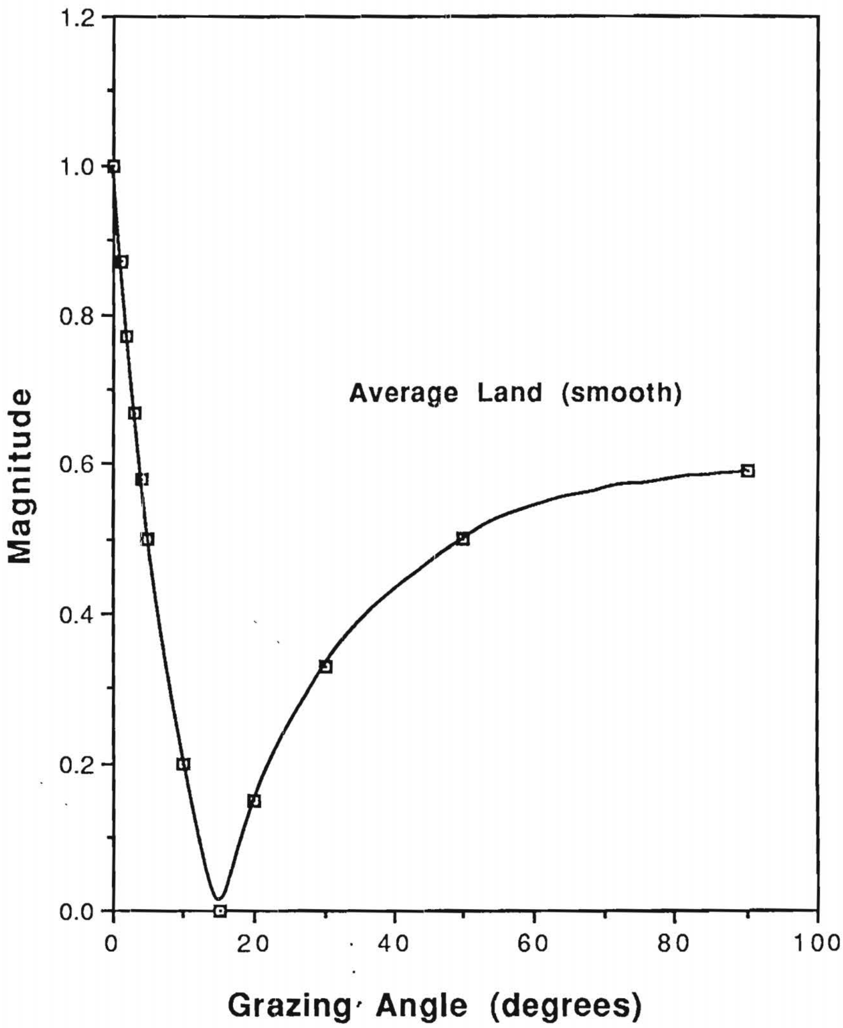

Figure 10. A graph of the magnitude of the vertical polarization reflection coefficient magnitude versus grazing angle for propagation over average smooth earth at 5 GHz.

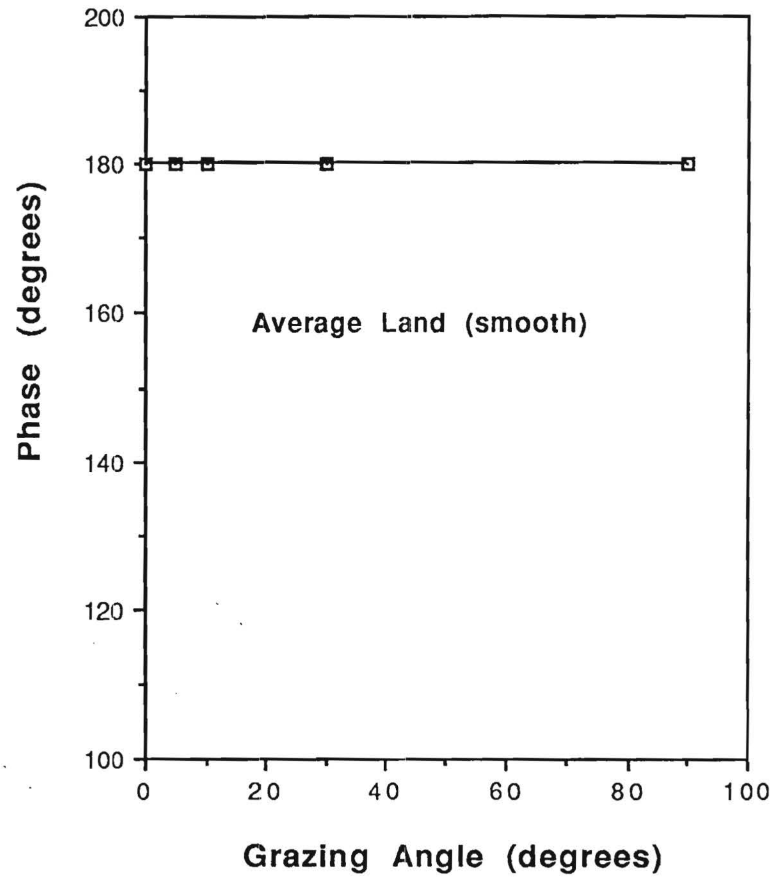

Figure 11. A graph of the phase of the horizontal polarization reflection coefficient magnitude versus grazing angle for propagation over average smooth earth at 5 GHz.

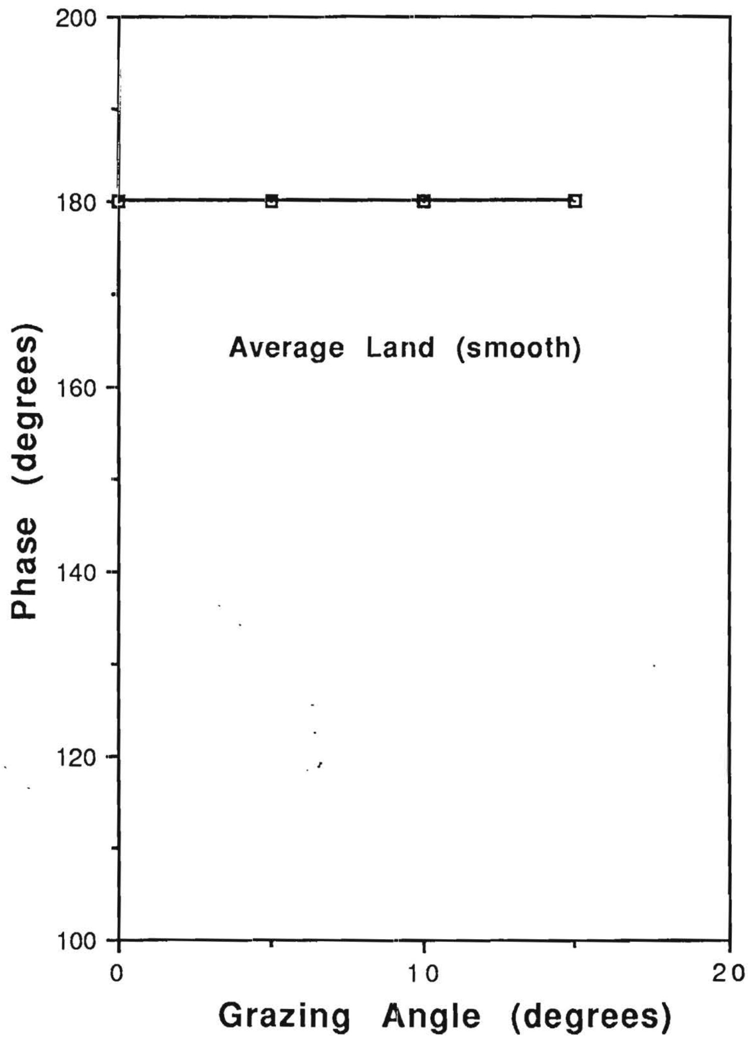

Figure 12. A graph of the phase of the vertical polarization reflection coefficient magnitude versus grazing angle for propagation over average smooth earth at 5 GHz.

Diffractive Obstacles

The man-made obstacles in the propagation path can both reflect incident energy and diffract it away from the preferred direction of propagation. The transmitter energy propagating along such a path could suffer significant attenuation because of these obstacles. Diffraction effects can be countered to a great degree by increasing the transmitting antenna height so that at least 60% of the first Fresnel zone is clear of any diffracting edges. Theoretical/empirical expressions for estimating diffraction losses are available (8), but must be adapted to the particular path and circumstances being analyzed; it would be difficult to provide a general value for this project at this time.

Vegetative Absorption and Reflection

The presence of greenery along the path poses significant concern with regard to absorption and reflection of incident energy, especially at the low angles of propagation appropriate for this study. The attenuating effect becomes greater as the frequency increases. The presence of moisture or dew will generally make the situation even more serious.

Incident Polarization

The amount of energy absorbed by experimental animals at an exposure site will be influenced by their orientation with respect to the incident field. The polarization of the incident field will have been altered to one degree or another along the propagation path, and would have to be measured at the exposure site.

Atmospheric Absorption and Rainfall

At the frequencies of interest to this project, atmospheric absorption and rainfall effects are negligible.

Atmospheric Refraction

At the frequencies (especially the lower frequencies) of interest to this project, atmospheric refraction can reduce the amount of transmitted energy reaching the exposure point by "bending" the propagating rays upward to the sky or downward to the ground. The amount of "bending" and the direction depends upon the refractive index gradient encountered. For this project, it would be anticipated that a downward "bending" would be more prevalent, though at this time it is not felt that refraction will be a significant concern.

Atmospheric Reflection

Atmospheric reflection can take place in the ionosphere in much the same manner as for the ground reflection phenomenon discussed above. The same equations apply when the appropriate constituitve parameters are substituted. At frequencies below approximately 100 kHz, the change in ionospheric electron and ion density within the distance of a wavelength is of such magnitude that it it behaves like an abrupt discontinuity in the medium; therefore, reflection of the incident wave takes place. For the frequencies of interest and the propagation regions for this project, atmospheric reflection is not of concern.

Atmospheric Ducting

Ducting of electromagnetic energy could be of significant concern in some propagation scenarios pertinent to this project. Ducting depends on the refractive index gradient in the region of the atmosphere through which the energy travels. The refractive index gradient is a function of the change in humidity and temperature with height above ground. Ducting, therefore, is influenced by the atmospheric and surface conditions of the propagation path and can vary as a function of the time of the day or the season. Duct thicknesses are on the order of 15 m and can, potentially, refract energy up and out of the duct, thereby reducing the amount of energy being brought to bear on the exposure point. Other ducting scenarios may be applicable as well, but this case points out the basic nature and effects of the ducting phenomenon. One compact expression for computing the specific attenuation, γd, due to ducting is given in the International Radio Consultive Committee (CCIR) Report 569-3 is climate-dependent and applies specifically to the amount of attenuation occuring for less than about 1% of the time (7).

$$\gamma_d = \left[c_1+c_2\log(f+c_3)\right]p^{c_4} \quad \text{dB/km}, \qquad (8)$$

where, f = frequency in GHz
p = the annual time percentage, and
c_1, c_2, c_3, c_4 are constants dependent upon the climate zone.

For instance, in a non-coastal or non-shore zone at a frequency of 500 MHz and an annual percentage time of 0.9%, the specific attenuation is 0.07 dB/km. Then, at a distance of, e.g., one statute mile or 1.61 km, a loss of approximatelty 0.11 dB would be experienced. At a frequency of 1 GHz, the path loss would increase to approximately 0.17 dB. All zones considered, a rough estimate of one-mile path loss due to ducting would fall generally in the range of 0.05 dB to 0.25 dB.

BIOLOGICAL IMPLICATIONS

The biological effects produced by a propagating electromagnetic field reacting with a human depend upon such factors as the carrier frequency, the polarization with respect to the long axis of the body, the pulse repetition frequency, or prf, (if pulsed transmission is being used), and the peak power density incident upon the subject.

The approach taken in this section was to theoretically determine the greatest range from a simulated transmitter site at which the field parameters conform roughly to the values generally felt to be sufficient for initiating effects which could be sensed by the subject and/ or begin to impair normal functioning. At distances less than this greatest range, the effects would become more pronounced and perhaps change in nature. Two regions of interest were treated.

The first was the lower to mid-UHF frequency range where skin depths on the order of 4 cm permit deeper deposition of EM energy (compared to L-band and higher frequencies) and, therefore, the possibility of bioeffects at locations other than just the skin. The second region was the L-band frequency range and above where EM energy deposition is primarily within 1 to 2 cm of the skin surface and can induce significant thermal stress.

Ghandi (9) has summarized in his book most of the important findings with regard to coupling electromagnetic energy to humans in the applicable resonant-frequency range. The matter of induced current distributions and whole body averaged specific absorption rates (SAR) in human models, with and without isolation from earth, are discussed from both theoretical and experimental perspectives. Ghandi's excellent summary includes empirical expressions pertaining to free-space irradiations at subject-specific resonant frequencies, and these were used to compute incident power densities needed to produce the lowest mean SAR required to initiate a given biological effect described in Table 10-1 of (9). In the latter table, a value of 6.0 W/kg is given as the threshold for perturbation of neurotransmitter levels in rats and this SAR value is the greatest value among the values specified for producing bioeffects in behavior, the central nervous system, hormonal levels, and the cardiovascular system: this means that were the subject to be irradiated at SAR levels which would initiate changes in the neurotransmitter levels, then the subject would also experience the other bioeffects as well. Further, it can easily be seen that in a given high power simulation, a bioeffect in, e.g., the central nervous system would occur at a shorter range than for the threshold for neurotransmitter effects, since the SAR is only 1.8 W/kg, or less than one third the SAR value for neurotransmitter effects.

Studies such as those summarized by Gandhi (9) and those reported more recently, e.g., by D'Andrea and Cobb (10), provide the basis upon which an SAR value of 4 W/kg was established for behavioral and physiological changes in experimental rats. D'Andrea and Cobb (10) dealt specifically with behavioral changes in rats with high peak power, pulsed fields at a frequency of 1.3 GHz, and reported confirmation of the 4 W/kg threshold level. Since the SAR value of 6 W/kg given in Gandhi's book for neurotransmitter level bioeffects was in excess of all the estimated threshold values for other important bioeffects, it was used as the starting point for estimating a threshold SAR value which could be used for humans as represented by the human prolate spheroid (HPS) model. Since humans have a superior thermoregulatory capability which can mitigate thermal consequences of EM exposure, a very rough estimate of twice the 6 W/kg value was used. The influence of other compensatory capabilities possessed by humans, body shape, and ambient temperature are not treated explicitly here due to their complicated nature, but may serve to elevate the SAR figure in order to produce the net (estimated) SAR of 12 W/kg. The important assumption here, to be explicit, is that the latter SAR will, indeed, produce the same effects in humans as in rats. This may be shown eventually not to be valid in part or in whole, but once a valid SAR is established, the methods used in this report may be used for recalculations. Various circumstances such as orientation of the subject at the time of irradiation, physical condition of the subject, ambient temperature, etc., might affect the validity of these estimates, but a "generic" case is presented here and it would require adjustment in each particular location to assess bioeffects which might occur in the course of HPM work at that location.

In the UHF range, the threshold SAR of 6 W/kg was divided by the SAR value computed from Table 10-1 or read from Figure 8-3 of Gandhi (9) for a given above-resonance frequency for the HPS model. This quotient then gives an estimate for the power density in mW/cm^2 required at incidence upon the HPS model to produce a 6 W/kg SAR. From this power density figure, the maximum range (from a given transmitter site) at which bioeffects might be experienced can be estimated. The equations of Table 8-1 and the graphs of Figure 8-3 in Gandhi's book were helpful in deriving SAR estimates for the HPS model in the above-resonant frequency range, and in particular, the lower microwave UHF range. The equations were limited in validity to about 460 MHz, but the graphs showed a rapid drop in SAR, with respect to frequency, beyond the resonant frequency to an approximately constant value into the microwave and millimeter-wave regions. Computations yielded SAR values for the HPS model of approximately 0.05 mW/g at 300 MHz and 0.033 mW/kg at 450 MHz. The corresponding values taken from the graphs were approximately 0.032 and 0.030, respectively. Therefore, using SAR values of 0.05 mW/g at 300 MHZ and 0.03 mW/g at 400 MHz, the computed incident power densities become 240 mW/cm^2 and 400 mW/cm^2, respectively.

At this point several assumptions were applied to the computation of the maximum range at which this power density would exist for a given site ERP. First, the range was computed on the basis of the transmitter antenna gain along boresight, i.e., the maximum gain in the antenna's radiation pattern. Thus, consideration of matters off-boresight and in the sidelobes were ignored in this treatment, but should be addressed in each individual simulation where the radiation pattern is characterized. Next, the effects of the terrain will be unique to each individual site and could not be applied meaningfully here in a quantitative way, but a review of the propagation section above will point out that multipath phenomena can severely weaken a signal at some point along the path as well as enhance it. It would be advisable to incorporate a path analysis for each simulation to address this concern. Finally, none of the other factors affecting propagation, and therefore the strength of the incident field, were included in the computations made here. Therefore, only free space propagation computations were used in deriving the range estimates.

In free space, then, estimates of the greatest range at which fields of sufficient strength to cause neurotransmitter level effects can be computed by using Equation (4). From Table 9, it can be observed that the 400 mW/cm^2 and 240 mW/cm^2 power densities can theoretically be created with very high values of peak power and antenna gain at ranges of approximately 5600 ft and 7300 ft, respectively, not withstanding propagation losses. The free space power density at one nautical mile for each of the transmitter arrangements is given for general reference.

At the higher microwave frequencies of interest, where the skin depth for human skin tisue is on the order of 2 cm, the approach used by Gandhi and Riazi (11) was utilized. The specific absorption rate applicable to cases where the energy deposition is confined predominantly, if not exclusively, to a small volume beneath the skin was computed. The method required computation of the quantity SAR(0) in mW/g at the surface where

$$SAR(0) = 2\, P_{inc} \frac{\left(1-|\rho|^2\right)}{\delta}, \qquad (9)$$

where	P_{inc} =	incident power density in mW/cm^2,
	ρ =	reflection of the skin for normal incidence, and
	δ =	skin depth in cm.

Since the SAR(0) is a function of frequency, several frequencies across the UHF, L-, and S-band (0.9 GHZ, 1.0 GHz, 2.0 GHz, 2.5 GHz, 3.0 GHZ, 3.5 GHZ, 4.0 GHz) were used in solving Equation 9 for the values of P_{inc} that would produce an SAR(0) of 4 mW/g and 8 mW/g at each frequency, where the latter value is the ANSI guideline for peak SAR values. For each value of P_{inc}, the free space range from hypothetical (but, representative) transmitter systems characterized by combinations of transmitter peak power or continuous wave power (CW) and antenna gains was computed. Tables 10 and 11 give the peak power simulation results for the case where SAR(0)= 4 mW/g and 8 mW/g, respectively, while Table 12 gives the results for the CW simulation results for SAR(0)= 4 mW/g. All three simulations indicate that, notwithstanding propagation losses, fields potentially

	Transmitter Antenna Gain (dB)							
	30				40			
Transmitter Power (MW)	1	5	10	15	1	5	10	15
Range (ft) for: 400 mW/cm^2	-	1050	1450	1800	1450	3250	4650	5650
Range (ft) for: 240 mW/cm^2	-	1350	1900	2300	1900	4200	5950	7300
Power Density at 1 Nautical Mile (mW/cm^2)	2	12	24	36	24	119	238	357

Table 9. Maximum ranges for which power densities of 400 mW/cm^2 and 240 mW/cm^2 can theoretically be achieved for various combinations of transmitted power and antenna gains. The power density at one nautical mile is also computed for each combination.

Frequency (GHz)	P_{inc} (mw/cm^2)	SAR(0) (mw/g)	Maximum Range at Which SAR(0) Occurs (ft)					
			Peak Power ERP (GW)					
			1	2	3	5	8	10
0.9	11.9	4.01	2650	3880	4650	6000	7600	8500
1.0	11.5	4.02	2750	3850	4700	6100	7700	8650
2.0	10.0	4.01	2900	4150	5100	6550	8250	9250
2.5	8.9	4.02	3100	4400	5350	6950	8750	9800
3.0	7.9	4.03	3300	4650	5700	7350	9300	10400
3.5	6.9	4.00	3500	5000	6100	7900	9950	11150
4.0	5.4	4.05	4000	5650	6900	8900	11250	12600

Table 10. Maximum ranges at which an SAR(0) of approximately 4.0 mW/g is achieved across the UHF, L-, and S- bands. The ERP values, from left to right, correspond to transmitting systems with peak power and antenna gain combinations of: 1 MW, 30 dB; 2 MW, 30 dB; 3 MW, 30 dB; 5 MW, 30 dB; 8 MW, 30 dB; 10 MW, 30 dB.

Frequency (GHz)	P_{inc} (mw/cm^2)	SAR(0) (mw/g)	Maximum Range at Which SAR(0) Occurs (ft)					
			Peak Power ERP (GW)					
			5	8	10	12	20	50
0.9	23.8	8.02	4250	5350	6000	6000	8500	13400
1.0	23.0	8.04	4300	5450	6100	6100	8650	13650
2.0	20.0	8.02	4600	5850	6550	6550	9250	14600
2.5	17.8	8.04	4900	6200	6950	6950	9800	15500
3.0	15.8	8.06	5200	6600	7350	7350	10400	16450
3.5	12.8	8.00	5800	7300	8200	7900	11550	18300
4.0	10.4	8.10	6400	8100	9050	8900	12850	20300

Table 11. Maximum ranges at which an SAR(0) of approximately 8.0 mW/g is achieved across the UHF, L-, and S- bands. The ERP values, from left to right, correspond to transmitting systems with peak power and antenna gain combinations of: 5 MW, 30 dB; 8 MW, 30 dB; 1 MW, 40dB; 12 MW, 30 dB; 2 MW, 40 dB; 5 MW, 40 dB.

Frequency (GHz)	P_{inc} (mw/cm^2)	SAR(0) (mw/g)	Maximum Range at Which SAR(0) Occurs (ft) CW ERP (GW)					
			0.1	0.2	0.3	0.4	0.5	0.75
0.9	11.9	4.01	2650	3800	4650	5350	6000	7350
1.0	11.5	4.02	2700	3850	4750	5450	6100	7450
2.0	10.0	4.01	2850	4100	5100	5850	6550	8000
2.5	8.9	4.02	3100	4400	5350	6200	6950	8500
3.0	7.9	4.03	3300	4650	5700	6600	7350	9000
3.5	6.9	4.00	3500	4950	6100	7050	7900	9650
4.0	5.4	4.05	4000	5650	6900	7950	8910	10900

Table 12. Maximum ranges at which an SAR(0) of approximately 4.0 mW/g is achieved across the UHF, L-, and S- bands. The ERP values, from left to right, correspond to transmitting systems with continuous wave (CW) power and antenna gain combinations of: 0.1 MW, 40 dB; 0.2 MW, 40 dB; 0.3 MW, 40 dB; 0.4 MW, 40 dB; 0.5 MW, 40 dB; 0.75 MW, 40 dB.

exceeding the 4 mW/g and 8 mW/g SAR figures might be generated during high power microwave work outdoors.

Summary

The preceding discussion on terrestrial propagation included the present availability and capabilities of high power pulsed and continuous wave radar transmitting systems. The free-space power densities for these high power systems was estimated and the terrestrial and atmospheric factors which modify the free space propagation analysis were briefly discussed. The free space power density estimates for a 15 MW source and a very high gain (45 dB) antenna computed at 500 ft increments out to 6000 ft (approximately one nautical mile) demonstrated the dramatic fall-off (inversely with range) to only 1.13 W/cm^2; terrestrial and atmospheric factors could reduce this figure significantly. On an SAR basis, it was shown that SAR values associated with the possibility of bioeffects can be achieved at these power densities as far out in range as approximately one nautical mile or greater, again discounting modifying propagation factors which must be assessed in context with the terrestrial and atmospheric conditions in the region of the high power transmitting system.

HPM INSIDE WORKING SPACES

Given the great variety of working space geometries and irradiation circumstances that could be encountered in HPM testing and operation, several basic exposure scenarios can be formulated and later modified for specific circumstances to generate theoretical simulation models and experimental evaluations. Rectangular waveguide concepts can be profitably exploited in the VHF and lower UHF frequency range to model general circumstances in which one end of work room might be opened. Cavity resonator concepts can also be employed to study cases where a room in completely closed (e.g., all doors closed and no windows) or where a door might be opened. As the frequencies of operation extend into the L-band and higher, free space propagation concepts become applicable. The following discussions develop these approaches and carry them to the extremes of very high power emissions.

Waveguides and Cavities

A rectangular room with one end opened can produce guided propagation of electromagnetic energy emanating from a point (or points) within the room. The point of emanation is referred to as the feed point, and its location influences the power that actually propagates through the guide. The frequency of the energy introduced into the guide at a feed point is important in determining the nature of the propagating field. Room geometry also influences the nature of the energy distribution within the rectangular guide: height and width in relation to the wavelength of the propagating energy influence the mode of the propagating energy; discontinuities in the walls, ceiling, and floor can generate evanescent modes of propagation which attenuate greatly within a few wavelengths of distance from the discontinuity; and the presence of dielectrics and reflective objects such as people, furniture, metal fixtures, etc., influence the nature of the propagating fields. Losses in the propagating energy can occur when the walls, floors and ceilings are composed of less than perfectly conducting materials. For "worst case" simulations, rooms could be coated or lined with materials of sufficiently high conductivity to adequately approximate perfectly conducting surfaces.

Figure 13 is a representation of a section of rectangular waveguide having an inner width of a (in the x-coordinate direction) and an inner height of b (in the y-coordinate direction). Propagation in this waveguide is assumed to take place along the longitudinal axis (the z-coordinate direction). The opened end (aperture) of the waveguide is shown facing outward from the plane of the page and the other end is closed (shorted) with the same, ideally perfectly-conducting material as the rest of the inner surfaces of the waveguide.

One way of coupling energy to the waveguide is shown in Figure 13, where a coaxial feed is placed in the upper wall at a distance (ideally) of one-half wavelength from the shorted termination. With this example of feed, the electric field vector has components only in the transverse (x-y) plane, i.e., only an x-component and a y-component, and propagates in the positive z-direction toward the aperture, where some of the energy will be transmitted into the the medium outside the waveguide and the rest reflected back into the waveguide. The accompanying magnetic field will have an x-component and a z-component. Because the E-field components are all in the transverse plane, the propagating wave of energy is said to be a transverse electromagnetic wave, or a TE wave.

An important operating parameter for a waveguide is its cutoff frequency: this is the frequency below which energy will not propagate to any significant degree. For the geometries shown in Figures 13 and 14, the waveguide cutoff frequency is given as

$$fc_{m,n} = \frac{1}{\sqrt{\mu\varepsilon}}\sqrt{\left(\frac{m\pi}{a}\right)^2+\left(\frac{n\pi}{b}\right)^2}\ , \qquad (10)$$

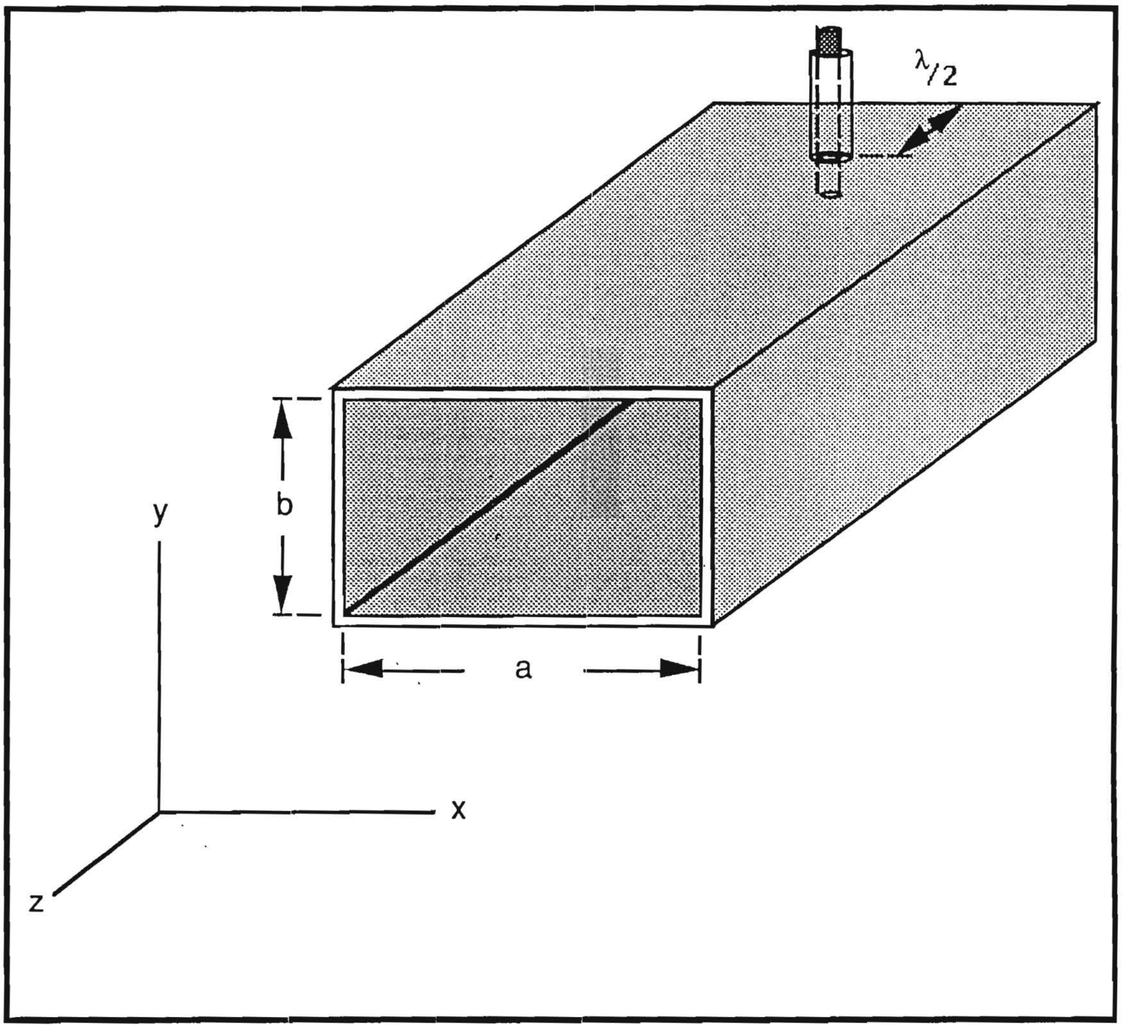

Figure 13. Rectangular waveguide powered by a probe inserted through the top surface along the longitudinal axis at a distance of one-half a wavelength.

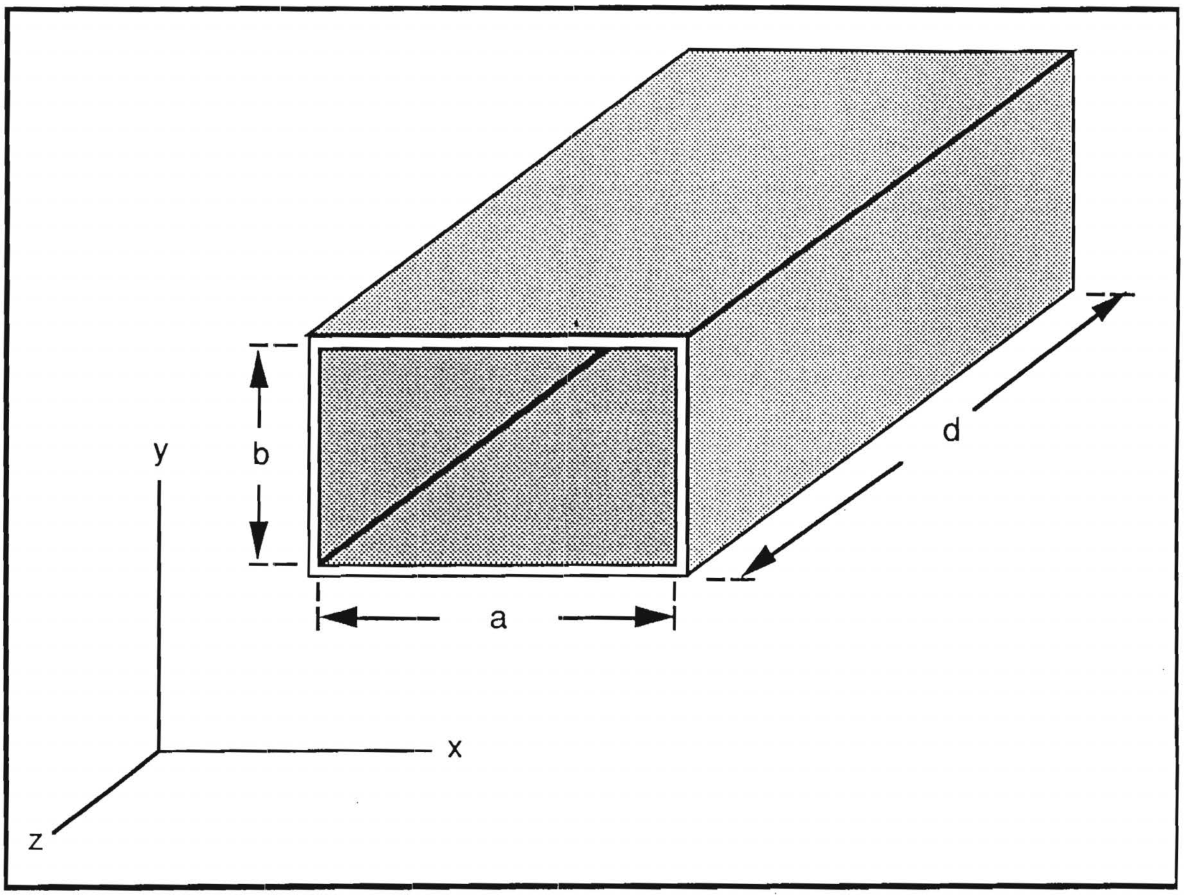

Figure 14. A "generic" waveguide/ cavity model for rooms and hallways in HPM work.

where m, n = 1,2,3,... and are called the mode numbers.

For a rectangular cavity, created from the waveguide by shorting the opened end with a conducting wall, the resonant frequency is given by

$$fc_{l,m,n} = \frac{1}{\sqrt{\mu\varepsilon}}\sqrt{\left(\frac{l}{2d}\right)^2+\left(\frac{m}{2a}\right)^2+\left(\frac{n}{2b}\right)^2}\ , \qquad (11)$$

where l, m, n = 1,2,3,... and are called the mode numbers.

The mode numbers m and n have the significance that they give the number of half-wavelengths of the electric field in the transverse dimensions x and y, respectively, within the waveguide. Since m and n can take on any positive integer values, there are obviously a large number (infinite, in fact) of modes which could possibly propagate in the waveguide. The mode corresponding to the lowest cutoff frequency, $fc_{m,n}$, is generally called the dominant mode for the waveguide. For the rectangular waveguide, this mode can be shown to be that for which m=1 and n=0, and it is given the designation TE_{10}. Dimensionally, it corresponds to a waveguide with a side ratio b/a = 1/2, and most practical waveguides are designed around this figure. For this case, only the E_y-component of the E-field exists, and it exhibits a half-cycle of sinusoidal amplitude variation across the x-dimension of the waveguide. The corresponding lowest order TE mode for the resonant cavity is TE_{101}

Rectangular (and cylindrical) waveguides can be designed for other modes of operation, and the field structures for these different modes are also well characterized. Since less-than-ideal circumstances are present in almost all practical design undertakings, theoretically-derived design parameters serve only as a starting point in waveguide system construction and moderate adjustments, based on such measurements as VSWR (voltage standing wave ratio), must ultimately be applied. For instance, were an experimental dielectric body, such as guinea pig or rat, placed within the waveguide, perturbation of the theoretically-derived operating parameters would occur. Knowledge of the field structure for a given mode of operation can be used to determine the location or locations of optimal coupling within the waveguide. The work of Chou, Guy, and Galambos (12) discusses these considerations briefly in regard to the design of a TE_{11} mode of operation of a cylindrical waveguide for optimal coupling of pulsed energy to guinea pig heads.

Given that the usual methods can be employed to optimize transmission within the waveguide, such matters of interest as energy levels that can be transmitted down the waveguide-modeled room, wall losses, evanescent modes, radiation through the opened-end aperture and apertures in the walls (e.g., opened doors) must be addressed; therefore, a brief theoretical treatment of the principles involved will be presented with the understanding that they must be applied in context with the specific geometry and physical make-up of each, indivdual HPM work room which is to be simulated with waveguide concepts.

Figure 14 depicts a "generic" room or long hall in a building. As a room, it would have a closing surface placed at the opened end and could be treated analytically as a cavity. As a working space for HPM work or as a hallway where energy from HPM work might travel, the walls, floors and ceilings could be constructed of common building materials which are highly transparent to microwaves, highly conductive metal materials, or materials possessing in-between properties. These properties are important along with the model's physical dimensions in establishing its responses to HPM energy introduced into them during the course of HPM work.

Table 13 provides operating modes and their associated resonant frequencies computed for several rectangular rooms of various sizes and a relatively short rectangular hallway. Note that for each room or hallway there are several modes which correspond to resonant frequencies in the human resonant range of approximately 60 MHz to 80 MHz. These values were computed for the "worst" case of completely enclosed spaces with highly conducting walls, ceilings, and floors. The discussion in the Terrestrial Propagation section regarding possible bioeffects for the above-resonant VHF and UHF frequency bands apply here as well.

As the frequency increases into the L-, S,- and higher frequency bands, the propagation becomes more free space in nature and the mode concept (for working space dimensions) can be abandoned. Also at the higher frequencies, the surface SAR concept (discussed in the Terrestrial Propagation section of this report) becomes important because of the small skin depth.

The working spaces used in deriving the modes and resonant frequencies are "generic" in nature: they are purely rectangular with no apertures (doors, windows, etc.), furniture, or occupants. As the generic models evolve into more practical models of actual working spaces, wall, floor, and ceiling discontinuities, metallic and nonmetallic furniture (e.g., bookcases, chairs, tables) and the presence of dielectrics (people) must be recognized for their perturbing effect on the operating characteristics derived (or measured) for the generic spaces. Discontinuities will transform some

Dimensions (ft)			Mode (TE)	Resonant Frequency (MHz
15	12	9	101	52.5
			111	75.8
	(Room)		210	88.3
			102	77.3
			211	103.4
			102	85.4
20	14	9	101	41.0
			111	68.3
	(Room)		210	70.1
			102	59.1
			211	88.9
			012	73.5
15	12	8	101	52.5
			111	80.8
	(Room)		210	88.3
			102	77.3
			211	89.9
			012	107.6
40	7	8	101	71.3
			111	94.2
	(Hall)		210	141.1
			102	74.5
			211	153.9
			012	66.2

Table 13. Resonant cavity modes and their associated resonant frequencies computed for several representative room sizes.

of the energy into evanescent modes (which attenuate to insignificant levels within a few wavelengths (13, 14) of distance from the discontinuity) and the presence of dielectrics will shift the resonant frequency to a lower value by an amount dependent upon the number of occupants and their locations. For example, the microwave oven modeling work by El-Deek et al. (15) showed that the introduction of a dielectric block dropped the TE_{111} mode resonant frequency from approximately 814 MHz to 550 MHz and the TM_{111} mode resonant frequency from approximately 814 MHz to 500 MHz. The dielectric block height (with respect to the cavity height) and the location of the block influenced the amount by which the resonant frequency was reduced for both TE and TM modes; these reductions were as great as 38.6% of the empty-cavity resonant frequency.

In estimating the TE mode powers that might be encountered, the "worst-case" situation of a generic room with discontinuity-free, perfectly-conducting walls was simulated. Dimensions of the room were taken to be 12 ft in width, 9 ft in height, and 15 ft in length, and the room was (hypothetically) coupled to the transmitter with coaxial cable such that the center conductor of the coaxial cable extended vertically down from the center-axis of the ceiling at a distance of $\lambda/2$ from the rear wall (see Figure 13). The actual distance of the coaxial probe from the rear wall in an experimental situation is a function of the impedance matching achieved for the specific workspace being modeled (13, 14). Nominally, this probe would be expected to extend down into the room a distance of approximately 50%-60% of the ceiling height, based on conventional resonant cavity analysis and, again, depend upon the measures taken for impedance matching. But, as the frequency increases, the probe length can be shortened and the energy imparted to the cavity or waveguide can be treated from the perspective (among others) of a radiating dipole antenna above a ground plane. Assuming a 50 Ω characteristic impedance for the coaxial line and taking the TE wave impedance of the air-filled room (cavity) to be on the order of 100 Ω, the voltage reflection coefficient, ρ, is computed to be 0.333. Using this value, an approximation of the amount of power supplied to the cavity through the coaxial line can be computed and a maximum power density can then be estimated on the basis of room height and width. Estimates of representative maximum power densities expected for the cases of high peak power and high CW transmitters were computed. These estimates did not take into account serious impedance matching, waveguide losses, or wall losses. Any efforts to match the impedance of the coaxial line to the waveguide impedance and to minimize losses would serve to maximize the amount of power entering and remaining 'in the room and, therefore, maximize the power densities. Table 14 gives the theoretical results for high peak power transmitters, assuming negligible coaxial losses.

Input Peak Power (MW)	Room Peak Power (MW)	Maximum Power Density (W/cm^2)
1	0.89	8.86
2	1.78	17.72
3	2.67	26.58
4	3.56	35.44
5	4.45	44.31
6	5.33	53.17
7	6.22	62.03
8	7.11	70.89
9	8.01	79.75
10	8.89	88.61

Table 14. Peak power and peak power densities in a 12 ft x 9 ft x 15 ft room fed from high peak power pulsed tranmitters by a coaxial probe.

The various tubes that might conveniently be employed in simulations of this type are those in Figures 8 and 9, which operate in the frequency range of 0.5 GHz to 3.5 GHz and at peak powers less than approximately 10 MW. The greater the transmitter power used, the greater requirement for support equipment (such as cooling equipment) and the greater the possibility of arcing, component damage, etc. The room sizes considered here are greatly protected from arcing by virtue of their large dimensions, but in the range of 5 MW and greater, serious arcing damage can be produced in the region of the probe, and this prospect must be considered in the design of the probe-ground plane region.

Table 15 gives the theoretical power and power density results for the case of high power CW simulations.

The high CW power Varian klystrons of Figure 6 are well-suited for experimental simulations of HPM working spaces for investigation of possible bioeffects. In particular, those operating at

Input CW Power (kW)	Room CW Power (kW)	Maximum Power Density (W/cm^2)
100	88.91	0.89
150	133.36	1.33
200	177.82	1.77
250	222.28	2.22
300	266.73	2.66
350	311.19	3.10
400	355.64	3.54
450	400.10	3.99
500	444.56	4.43

Table 15. Continuous (CW) power and CW power densities in a 12 ft x 9 ft x 15 ft room fed from high CW power transmitters by a coaxial probe.

the 250 kW level or higher are theoretically capable of producing power densities on the order of several watts per square cm in the generic room of this example (12 ft x 9 ft x 15 ft). Thompson-CSF produces high CW power klystrons capable of outputs in the MW range at UHF frequencies and 0.5 MW at 3.7 GHz. The 1 MW devices would serve to double the values in the last row of Table 15.

The computations made in Tables 14 and 15 apply well to any room with dimensions close to those of the example used. The basic computation sequence is:

1. Compute the voltage reflection magnitude

$$\rho = \frac{Z_L - Z_0}{Z_L + Z_0}, \tag{12}$$

where Z_L= wave impedance of room, and
Z_0= characteristic impedance of feed

2. Compute the power entering the room

$$P_R = P_{inc}\left(1-|\rho|^2\right) \tag{13}$$

where P_{inc}=the incident power from the transmitter

3. Divide P_R by the cross sectional area of the room normal to the direction of propagation.

In considering rooms which have microwave-transparent boundaries, the powers entering the rooms computed in Tables 14 and 15 can be thought of as propagating in free space. Whether the subject would experience near-field or far-field exposure would depend on the radiating element dimensions, the wavelength of the energy, and the location of the subject in the room. The far-field values can be computed using Equation (4) without concern for the modifying environmental factors discussed in the Terrestrial Propagation section. Other feeds available for theoretical or experimental simulations are loops and waveguides. Loops, which couple into the magnetic field, should be positioned horizontally out from the center of the rear wall and into the nearest magnetic field maximum for optimal flux coupling. For launching a TE mode, the plane of the loop should be parallel to the floor and ceiling. The distance which a loop should extend into the room is a function of the measures taken to accomplish matching. Waveguides are capable of handling higher power levels than the coaxial cables used for probes and loops, and cylindrical waveguides are superior to rectangular waveguides in this regard. The aperture formed by the junction of the waveguide with the room (cavity, waveguide) is flush and, therefore, does not protude into the room. The aperture can be designed to achieve good impedance matching.

The design of physical replicas to model HPM workspaces for bioeffects studies can take on an arbitrary degree of complexity. An unshielded room with microwave-transparent (or low-loss) walls should include simulation of any external (to the room) microwave reflectors which could return "leaked" energy as well as energy entering the room from any external transmitters. The inclusion of wall discontinuities, bookcases, furniture, etc., could contribute to more accurately simulated field configurations. It is conceivable that the physical model can begin with a rectangular room (ordinarily) with dimensions equal to that of the HPM workspace of interest. The materials for the walls, floor, and ceiling can be made to very closely approximate the electrical characteristics (permittivity, permeability, conductivity) needed. The inclusion of apertures such as doors and windows would add more validity to the model. The feed type can be selected and introduced at the desired position within the modeled room; any of the three feed types may be used as necessity dictates. The power levels, frequencies, pulsewidths and pulse repetition frequencies can then be chosen to simulate the particular HPM devices used for that workspace. The fields can be mapped in this carefully designed room, and valuable insight into the field configurations can be achieved. At this point, dielectric "phantoms" could be introduced into the room to experimentally determine SAR levels and correlate them with the field distribution. The next step would be to incrementally introduce significant discontinuities such as recesses in the walls (or protuberances from them), bookcases, tables, instrumentation, etc., similar to those in the HPM workspace while measuring SAR in order to begin to ascertain the bioeffects significance of each of these components.

The large dimensions of the hallways and rooms, when compared to UHF or microwave wavelengths, create "overmoded" or "oversized" waveguide propagation conditions when operated at frequencies well above typical cutoff frequencies. For instance, a hallway with a width of 2 m and a height of 3 m would have a theoretical cutoff frequency of 75 MHz. Therefore, energy at frequencies in the UHF range (300 MHz-1 GHz) and higher could propagate in an overmoded waveguide environment. Waveguides operated in the overmoded condition are capable of handling significantly greater power (by approximately an order of magnitude) than that supported by the waveguide when operated closer to cutoff (16). For waveguides filled with dry air, the peak power which can be supported is limited by the dry air breakdown electric field value of 2.9 x 10^6 V/m. This value is the theoretical limiting value that the sum of incident and reflected electric fields may reach at a point within an air-filled waveguide before arcing is initiated. The large transverse dimensions of oversized waveguides permit greater maximum electric field strengths to be achieved before the breakdown gradient is reached and, therefore, greater power handling. For a waveguide with width a and height b, the theoretical peak power for the TE_{m0} or TE_{0n} can be calculated by

$$P_{max} = 5.58 \times 10^6 \, ab\sqrt{1-\left(\frac{\lambda_o}{2a}\right)^2}, \tag{14}$$

For instance, the theoretical maximum peak power for the TE_{10} mode with a=2 m and b=3 m operated at 1 GHz would be 33.4 GW and the peak power density would be approximately 557 kW/cm^2. For the TE_{mn} modes, the appropriate equation is

$$P_{max} = 4.43 \times 10^8 \, ab\beta_{mn}\lambda_o\left[\left(\frac{m}{a}\right)^2+\left(\frac{n}{b}\right)^2\right]\left[\left(\frac{b}{n}\right)^2+\left(\frac{a}{m}\right)^2\right], \tag{15}$$

where $$\beta_{mn} = \sqrt{\left(\frac{\lambda_o}{2\pi}\right)^2-\left(\frac{m\pi}{a}\right)^2-\left(\frac{n\pi}{b}\right)^2} \; . \tag{16}$$

The large dimensions of overmoded waveguides also enhance the average power capability of the waveguides. The average power capability is determined by the temperature rises due to the waveguide conductor and dielectric components. The major factors influencing the average power are the attenuation in the waveguide, the surface area of the waveguide, and the temperature of the air bathing the inner and outer regions of the waveguide. The average power handling capability is a heat balance matter in which heat generated by losses in the guide walls is reduced by heat-reduction mechanisms such as conduction, convection, and thermal radiation. The heat reduction can be enhanced by increasing the surface area of the guide (overmoding) and by supplying cooled air to the guide.

Since real rooms and hallways possess discrete or continuous geometric irregularities, or discontinuities, such as changes in the transverse dimensions, changes in directions of the hallways, tapers in the hallways or rooms, etc., mode conversions between modes already in propagation and higher modes can occur. Energy from the generated modes can be coupled into these modes. When the distance between two discontinuities is an integral number of guide half-wavelengths for one of the generated modes, where the guide wavelength is given by

$$\lambda_g = \frac{\lambda_o}{\sqrt{1 - \left(\frac{f_c}{f}\right)^2}}, \qquad (17)$$

where f_c is the cutoff frequency and f is the operating frequency above cutoff, then a trapped-mode resonance can occur in that region of the waveguide. Thus, workspace irregularities can generate a rich mixture of modes which can propagate or resonate as well as evanescent modes which attenuate rapidly within a few wavelengths of their originating site.

Since high power microwave equipment operated within laboratory rooms can produce overmoded conditions, peak and average field levels potentially harmful to personnel may be generated. These fields would not be expected to reach the maximum possible levels, but with a variety of equipment the summed fields could reach thermally harmful levels over a short period of time.

Another concept to consider is that of energy traveling down a hallway or long room (with conductive walls, ceiling floor) which is open to the outside. As microwave energy travels down this waveguide it loses energy and the remaining energy reaching the opening encounters a rectanular aperture with a theoretical gain of 31.5 dB at 1 GHz based on Equation (1). Taking the largest peak power case of Table 14 for an example, 8.89 MW enters the waveguide through the feed and travels toward the aperture. Discounting waveguide losses, reflections, and refractions at the aperture-open space interface, and the effects of the ground plane formed by the earth's surface outside the aperture, a free space ERP of 12.45 GW is transmitted into the open. At a range of 6000 ft (approximately one nautical mile), the power density (for free space) would be 0.372 W/cm^2. Estimates of the power densities at shorter distances can be computed using Equation (4). The same concerns about SAR levels encountered in the Terrestrial Propagation section would apply here.

Summary

The preceding discussion treated situations in which HPM work might be performed within rooms with walls, floors, and ceilings which might be either conductive or microwave-transparent. Waveguide and resonant cavity concepts were applied at the appropriate frequencies for conductive room boundaries, and free space theory was applied for the higher frequencies and for nonconductive rooms and halls. For the case of spaces with conductive boundaries, it is possible to generate in a controlled manner enormous pulse and CW power densities over the range of microwave frequencies with the capabilities of the transmitter tubes presented in this report. Thus, the possibility of bioeffects of inadvertent high power emissions can be simulated either in an anechoic chamber or in replicate models of specific workspaces.

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